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Technical Report No. 4

APPLICATION OF ELECTRON SPIN ECHO RESONANCE PHENOMENA

by
M. M. Siera

Contract NOnr 2541(00)
Project NR 048-125

June 1964
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LOCKHEED MISSILES & SPACE COMPANY
A Group Division of Lockheed Aircraft Corporation
Sunnyvale, California

TECHNICAL REPORT NO. 4

PRÉCIS

Title: "Application of Electron Spin Echo Resonance Phenomena," M. M. Siera, Technical Report No. 4, June 1964; Contract NOnr 2541(00), Project NR 048-125.

Background: The Electronics Sciences Laboratory of the Lockheed Missiles & Space Company is studying the application of microwave spin echo phenomena for use as a microwave pulse delay line in such areas as high-speed computer memories and advanced radar systems. With the method of electron spin echo resonance, microwave energy in the form of pulses can be serially stored and recalled at an arbitrary later time within the relaxation time of the spin system.

Condensed Report Contents: A general description of the spin echo resonance phenomena in paramagnetic electron systems is given and a basic analysis determining some engineering parameters for the design of an electron spin echo module in a microwave device is presented. The use of slow wave structures to couple microwave power to the spin system is investigated in some detail. A number of possible applications of electron spin echo resonance phenomena are discussed with particular attention to computer memory possibilities. An engineering approach attempting solution of problems pertaining to several of these applications is suggested.

For Further Information: The complete report is available in the major Navy technical libraries and can be obtained from the Defense Documentation Center. A few copies are available for distribution by the author.

FOREWORD

This document describes work done by the Electronics Engineering organization of the Lockheed Missiles & Space Company during a feasibility study covering possible applications of the Electron Spin Echo Resonance Phenomenon.

This study was conducted under Office of Naval Research Contract NOnr 2541(00), Project NR 043-125.

ABSTRACT

A general description of the spin echo resonance phenomenon in paramagnetic electron systems is given and a basic analysis determining some engineering parameters is presented. The use of slow wave structures is investigated and a number of possible applications of the electron spin echo resonance mechanism are discussed. An engineering approach attempting the solution of problems pertaining to several of these applications is suggested.

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SECTION 1

INTRODUCTION

An experimental program to develop laboratory methods for studying electron spin echo phenomena at microwave frequencies has been underway at the Electronic Sciences Laboratory of the Lockheed Missiles and Space Company for several years.

In the course of this program, pulsed electron paramagnetic resonance instrumentation operating at microwave X-Band frequencies (9.3 Gc) has been developed for direct studies of paramagnetic relaxation processes, for variable frequency paramagnetic resonance spectroscopy, and for studies of microwave spin echo memory functions simulated by storage and read-out of multidigit pulse groups in paramagnetic systems.

Spin phase memory time and spin-lattice relaxation time measurements utilizing the spin echo technique have been carried out in a number of paramagnetic materials, spin echo phenomena from pure crystalline electric field interactions have been observed, and preliminary multipulse spin echo storage functions have been obtained in certain crystal configurations under zero magnetic field conditions.

The results of recent experiments and investigations, e.g., high modulation frequencies, low power requirements, extended storage time and pulse script read-out in normal or in inverse order -- all in the absence of external magnetic fields, appeared promising enough to analyse possibilities of applications based on the electron spin echo resonance phenomenon.

The Electronics Engineering Organization of the Lockheed Missile and Space Company, therefore, started a preliminary feasibility study in November 1963, with the intent to:

A. Evaluate the results of the activities of the Electronic Sciences Laboratory of the Lockheed Missiles and Space Company in the area of electron spin echo resonance phenomena on the basis of published reports, experiments and demonstrations.

B. Investigate potential applications of these phenomena as memory elements delay lines, etc., in computers and allied fields.

C. Submit a report describing the feasibility of the design and development of devices using the spin echo module (SEM).

A and B were completed during November and December 1963, and C is submitted in this document which contains a general description of the electron spin echo resonance phenomenon and a basic analysis of the spin echo module (SEM). This analysis presents some of the parameters on which the engineering feasibility study was based. Since it recommends the use of helices for the accommodation of the active crystal, a general evaluation of slow wave structures is included in this report. Several possible applications of the SEM are then discussed and an engineering approach is indicated.

The cooperation and valuable contributions to the study and to this report by M. A. Fischler, F. J. Janza, D. Kaplan, H. Katzman, T. P. Murphy and K. R. Spangenberg are herewith gratefully acknowledged.

SECTION 2

GENERAL DESCRIPTION OF THE ELECTRON SPIN ECHO RESONANCE PHENOMENON (ESERP), (REF.I)

The physical description of spin echo free precession phenomena is essentially the same for electrons as for nuclei. It has been developed in detail by Hahn[1] and others[2] from a fundamental viewpoint. Application of nuclear spin echo phenomena for information storage purposes has been studied by two groups[3,4]. The essential features of paramagnetic spin echo formation may be summarized thus:

A paramagnetic (electron) sample is contained in a microwave structure which provides a means of concentrating an electromagnetic field in the region of the sample. The electron spins of the sample are oriented either by means of a strong Zeeman dc magnetic field, or by the presence of internal crystalline electric field interactions, or both. The resultant magnetization of the sample, M_o, due to the Boltzmann excess spin population in the lower energy state is in equilibrium aligned along the polarizing axis of the internal or external field. The spin system can absorb energy from a radiation field at its Larmor frequency. The microwave structure containing the sample is oriented so that the magnetic component of the radiation field rotates in a plane transverse to the axis of polarization. Application of a microwave pulse of duration, t_i, at the Larmor frequency will tip the macroscopic magnetization from its normal orientation toward the transverse plane. A rotation of $\frac{\pi}{2}$ radians may be accomplished if the condition $\gamma_e H_1 t_i = \frac{\pi}{2}$ obtains, where γ_e is the effective electron gyromagnetic ratio and H_1 is the amplitude of the microwave magnetic field. The pulse duration is assumed to be short relative to the electron thermal and phase memory relaxation times, T_1 and T_2, respectively.

Following cessation of the microwave pulse, the macroscopic magnetization precesses about the axis of polarization inducing a rotating magnetic field, H_{fp}, in the microwave structure. This field lags the precessing magnetization by $\frac{\pi}{2}$ radians. The precessing magnetization and its resultant radiation field diminish in amplitude with time due to angular dephasing of the component spins contributing to M_o. This dephasing proceeds because of a distribution in precessional frequencies

over the sample associated with the resonant linewidth, $\Delta\omega$. There is hence a free precession signal following the pulse of duration $t_e \sim \frac{1}{\Delta\omega}$. The spins, however, preserve their relative phases for a time T_2 (phase memory time) which is usually much greater than t_e. T_2 is roughly a measure of the time required for spins to scramble their relative spectral positions due to dynamical (time varying) electron-electron and electron-nuclear spin-spin interactions. A second pulse of amplitude sufficient to rotate the entire spin ensembly by π radians applied at a time τ will give rise to constructive interference of the dephased spins provided τ lies in the interval $t_e < \tau < T_2$. This pulse may be regarded as flipping over the "pancake" of spins which exists in the transverse plane at a time $t > t_e$. The resultant signal from the $\frac{\pi}{2}$-π pulse sequence, separated by a time, τ , will occur at a time 2τ following the first pulse. This signal is popularly termed a "spin echo."

It may be regarded quite properly as the first pulse delayed or stored for a chosen time interval and recalled on command by the second pulse.

SECTION 3

BASIC ANALYSIS OF AN ELECTRON SPIN ECHO MODULE (SEM), (REF. II)

The essential element in an SEM is a suitable paramagnetic material contained in a microwave structure designed to subject the material in an efficient manner to the magnetic component (H_1) of a microwave pulse. The microwave structure must also couple spin echo signals (due to precessing coherent magnetization) to the microwave transmission line. Schematically, we may picture a single spin echo memory element as a one-terminal device, with input and output at the same terminal associated with energy flow in opposing directions. A cyclic device (microwave circulator) may be used to physically separate input and output terminals. Other means of isolating input and output coupling are possible depending upon the microwave structure employed. Figure 1 illustrates the general features of such a single element.

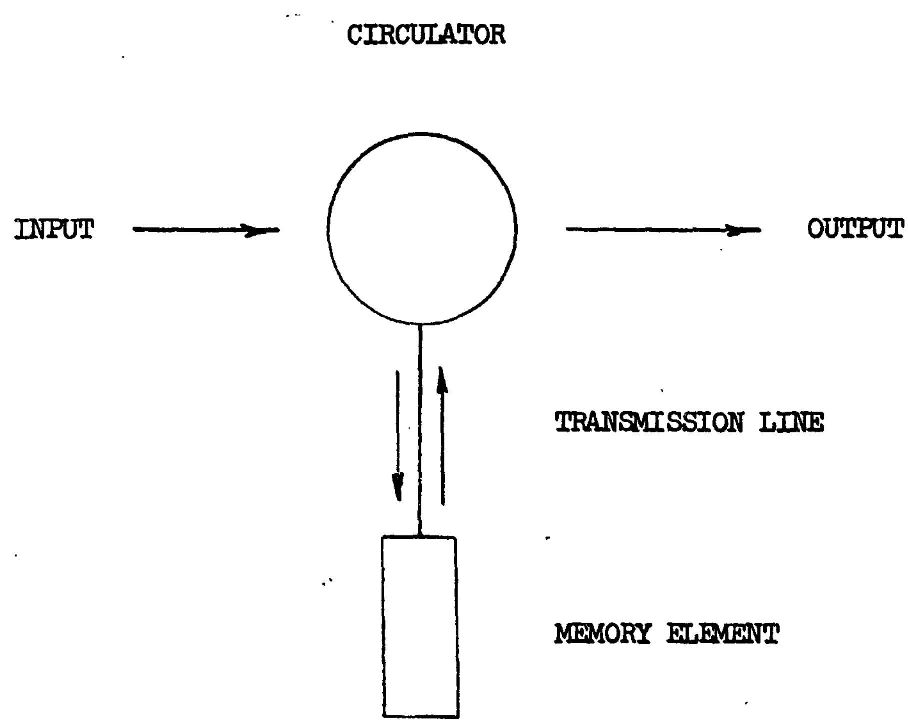


FIGURE 1

An example of an alternate possibility is shown in Figure 2. In this case the input is separated from the output by means of coupling techniques to the sample structure. This could, for example, be accomplished by coupling to different modes of a helix, using the sample to absorb power from one mode and return it in another.

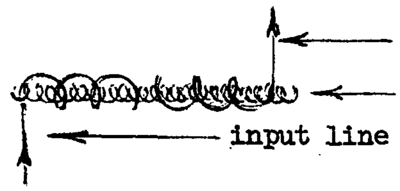


FIGURE 2

The requirements for the sample structure, per se, are the following:

1. Maximum H_1 for a given power input.

2. Uniform H_1 over entire sample volume.

3. Spatial separation of H_1 (magnetic) and E_1 (electric) field modes of e-m field, with the sample contained in the H_1 region. (Structures which have energy density predominantly in the magnetic (H_1) field throughout the volume are theoretically possible).

4. Maximum power delivered to microwave transmission line for a given sample magnetization, M.

5. Bandwidth not less than the physical bandwidth of the paramagnetic material.

6. Unity filling factor.

Either resonant structures or slow wave structures fulfill these requirements. We shall show that a typical slow wave structure appears to be more attractive than a typical resonant structure later in these notes.

Serial type storage of a microwave pulse script (PCM) with <u>either</u> first in-first out <u>or</u> first in-last out type information handling is possible with the spin echo phenomenon. Pulse amplitude coding is also possible with this phenomenon, but

will not be considered. To constitute a computer word, a number of elements equal to the number of bits in the word are required. These are then arranged on separate channels with parallel read-out of all the bits in a given word and serial read-out of the words. Other array systems may also be possible.

In "first in-last out" storage the capacity and storage time are both limited by the spin phase memory time, T_2, of the physical system. In first in-first out storage the capacity is limited by T_2, while the storage time is limited by T_1, the spin-lattice relaxation time. This is illustrated schematically in Figure 3. Figure 3(c) illustrates the use of cyclic first in-last out storage to provide first in-first out storage. This could, for example, be accomplished by circulating serial information back and forth between two spin echo stores.

Memory applications of ESERP have previously considered in detail only storage in magnetic interactions in nuclear spin systems. We are concerned here with electron spin systems and particularly with natural crystalline electric interactions in such systems. An external magnetic field is not used in this case. The analytical treatment of bit capacity does, however, involve the same general type of physical considerations since we are still dealing with magnetic transitions in a system characterized by a magnetic moment. In general for electron systems the resonant frequencies (frequency of digitalized microwave carrier in storage applications) are in the microwave region, the bandwidths are several orders of magnitude broader than in the nuclear case, and the available magnetization, several orders of magnitude greater. The size of the memory element, per se, may be expected to be several orders of magnitude smaller than that appropriate to nuclear spin systems. Cryogenic operation, usually of liquid helium temperatures, will probably be required for a SEM. Polycrystalline (powdered) materials may be used in zero magnetic field.

For utilization of a microwave memory element in a computer system processing information in a baseband code frequenc, conversion access circuitry is necessary. As one goes to higher microwave frequencies, the state-of-the-art is progressively less advanced. Such conversion is now possible with reasonable efficiency at microwave X-Band, the frequency region appropriate to the material we now have (Ca, Ce) F_2. For use with microwave carrier computers (non-existent), this is a compatible memory element and no frequency conversion is necessary.

This figure illustrates PAM
while actually PCM would be used.

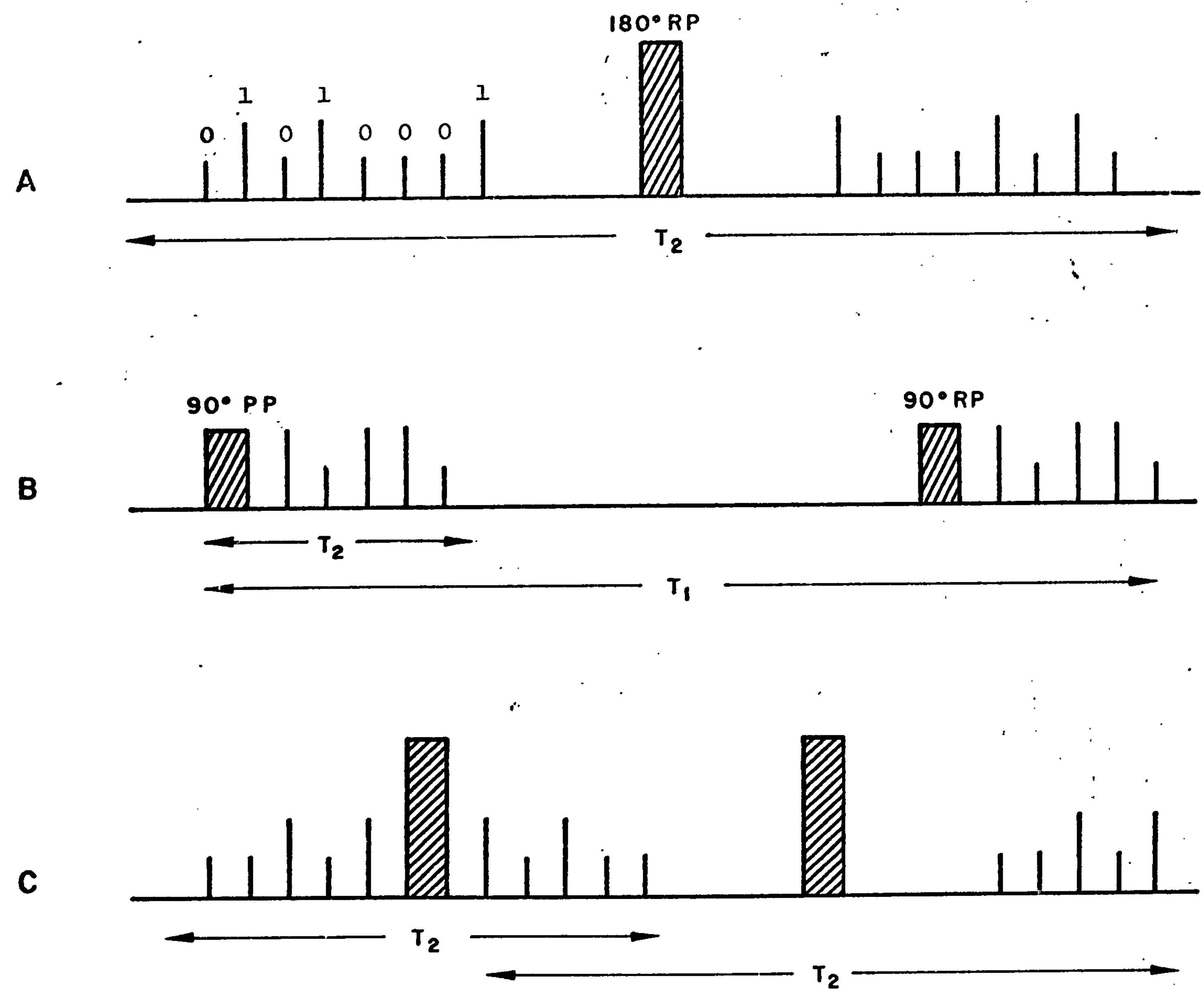


FIGURE 3

We proceed to calculate the properties of a resonant (cavity) structure and helix slow-wave structure as they pertain to the ESERP. It is convenient to assume that the paramagnetic sample is polarized in an external magnetic field for purposes of calculation. The results are quite valid for zero field interactions.

We assume a paramagnetic sample of specific magnetization, M, where M is given by

$$M = \frac{\gamma_e^2 \hbar^2 N H_o}{4kt}$$

Here

γ = gyromagnetic ratio of electron 2×10^7

$\hbar$ = Plank's constant 10^{-27}

N = number of ions/cm^3

H_o = magnetic field in gauss

k = Boltzmann constant

T = absolute temperature

We wish to calculate the power delivered to a transmission line in a spin echo experiment assuming a $\pi/2$ pulse, i.e., one information pulse (and spin echo) utilizing all the available magnetization, M. We calculate the signal strength due to the precessing magnetization, M, following a $\pi/2$ pulse, due to the existence of a coherent moment, M, immediately following the pulse. This magnetization will give rise to a microwave magnetic field H_r lagging in phase by 90^o in the transverse plane, the precessing moment M. (See Figure 4)

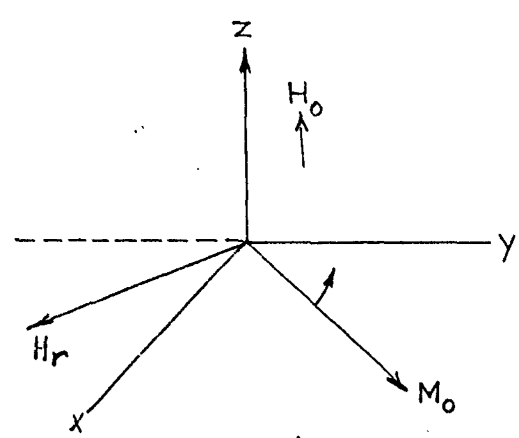


FIGURE 4

This is the so-called radiation damping field. The signal power in a spin echo experiment is associated with this radiation damping field. We note that we may write the torque equation:

$$\left(\frac{dM}{dt}\right)_r = \gamma_e H_r \times M \qquad \text{where} \quad \left(\frac{dM}{dt}\right)_r$$

represents the time rate of change of M due to the effect of H_r only. The change of the magnetic energy of the system due to this effect is given by

$$\frac{d}{dt}\left(H_o \cdot M\right)_r = H_o \left(\frac{dM}{dt}\right)_r = \gamma_e H_o H_r M$$

H_r is related to M by a constant of proportionality which depends on the properties of the microwave structure. We write

$H_r = kM$ and then

$\frac{d}{dt}\left(H_o \cdot M\right)_r = \omega_o \; k \; M^2$ (k to be determined) this is the power radiated per unit volume of material.

The power radiated by a sample of volume, v_s, is then

$$P_r = \omega_o k M^2 \, V_s \qquad (1)$$

We evaluate k for a cavity and for a helix.

For a cavity, the power * lost in the walls and delivered to the transmission line (Perfect coupling) is

$$P_r = \omega_o \, V_c \, \frac{(2H_r)^2}{8\pi Q} \qquad (2)$$

due to a field, H, of amplitude H_r

V_c = cavity volume

equating (1) and (2) we find

$$k_{cav.} = 2\pi Q \; V_s/V_c \qquad V_s/V_c = \text{filling factor} = \eta$$

or - for a cavity

$$P_r = \omega_o 2\pi Q \frac{(V_s M)^2}{V_c} = \frac{\omega_o 2\pi Q}{V_c} (\bar{M})^2$$

where

$$\bar{M} = MV_s \text{ (total magnetization of sample)}$$

so we have

$$(P_r)_{cavity} = \frac{\omega_o 2\pi Q}{V_c} (\bar{M})^2 \qquad \text{c.gs.}$$

$$k_{cavity} = 2\pi Q \eta \qquad (3)$$

For a helix (Ref. 1), optimized for uniform axial mode properties * at center X-Band.

$$(P_r)_{helix} = 10^6 H_r^2 \quad \text{c.g.s.}$$

* d $\cong$ 1.5 mm (diameter) chosen to make

n $\cong$ 20 turns/in. $\beta_a \sim 1.3$

where β = helix propagation constant.

$\beta = \frac{2\pi}{\lambda_h}$ λ_h = helix wavelength,

Then for <u>this</u> helix we have:

$$k_H = \frac{\omega_o V_s}{10^6}$$

$$(P_r)_{helix} = \frac{\omega_o^2}{10^6} (\bar{M})^2 \quad \text{c.g.s.}$$

For fixed $\bar{M}$ the ratio of power delivered to the transmission line by a helix to that by a cavity is

$$\frac{\omega_o^2}{10^6} \Big/ \frac{\omega_o 2\pi Q}{V_c} = \frac{\omega_o V_c}{2\pi 2Q 10^6} = R$$

for a cavity $Q \sim 100$ $\Delta_f \sim 100$ M_{cs} at $f = 10$ Gc

and $V_c \sim 1$ cm^3

we find:

$$R = \frac{10^{10} \cdot 1}{10^8} \sim 100$$

It is also seen that

$$\frac{(H_1)_{helix}}{(H_1)_{cavity}} = \sqrt{R} \quad \sqrt{\frac{P_{helix}}{P_{cavity}}}$$

so that, for equal input powers, $\frac{(H_1)_{helix}}{(H_1)_{cavity}} = 10$ in the above example.

For a typical sample material

$$M = 10^{-3} \text{ c.g.s.}$$

Taking $V_s = 10^{-2}$ cm^3 (a reasonable volume for an X-Band helix)

we have $M = 10^{-5}$ c.g.s., or for a single pulse, using all of M

$$(P_r)_{helix} = \frac{40 \times 10^{20}}{10^6} \times (10^{-10}) \times 10^{-7} \text{ watts}$$

$$\underline{P_{r_{helix}} \sim 40 \text{ milliwatts}}$$

It is of interest to calculate also the power required to produce a $\pi/2$ command pulse.

In general, the pulse angle Θ is given by

requiring $\Theta = \pi/2$ and taking $t\,\omega \sim 2 \times 10^{-8}$ sec.(pulse duration 20 nanoseconds)

$$H_1 \cong \frac{\pi/2}{4x10^7 x10^{-8}} \sim \frac{10\,\pi}{8} \sim 3 \text{ gauss}$$

For this particular helix

$$P = \frac{H_1{}^2}{10} \quad \text{watts}$$

$P \cong 1$ watt for a $\pi/2$ pulse in this example. Actual power requirements will be reduced by approximately a factor of 10 for some zero field systems because of higher effective values for γ.

It will be shown in the next section that the ideal amplitude for an information pulse in a train of N echoes (bits) is given by $\sin \Theta \sim \frac{1}{\sqrt{N}}$

Assume $N \cong 400$, then $\Theta \sim \sin \Theta = \frac{1}{20}$

and for a pulse of this amplitude

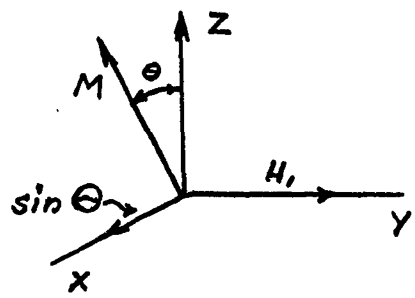
$H_1 \cong 0.1$ gauss

then

$P \cong \frac{10^{-2}}{10} \sim 10^{-3}\,\omega$ for an information pulse. Again, a reduction at a factor of 10 may be expected.

We now calculate bit capacity in terms of spin phase memory time, memory speed, and available signal power. In a memory application in which a large number of bits are stored, the available spin magnetization, M, is divided up approximately equally among the total number of bits. Assuming information pulses of equal amplitude, we wish to derive a general expression for information echo amplitude

for the nth echo in a group of N echoes. Consider Figure 5.



Assume M = 1

FIGURE 5

A pulse of angle θ will give rise to an echo of amplitude $\sin\theta$ in the absence of any additional pulses and neglecting relaxation time effects. A second pulse of angle θ will modify the first magnetization component by the factor $\sim \frac{1+\cos\theta}{2} \sim \cos^2\theta/2$ because of magnetization extracted from the transverse plane. Succeeding pulses will repeat the same process giving rise to a term $(\cos^2\frac{\theta}{2})^{N-1}$ for the first echo or, more generally, $(\cos^2\frac{\theta}{2})^{N-n}$ for the nth echo. Furthermore, note that the available magnetization is reduced by a factor $\cos\theta$ for each successive pulse. A general expression for the amplitude of the nth echo for first in-last out storage is:

$$f(\theta, n, N) = \sin\theta\,(\cos^2\frac{\theta}{2})^{N-n}\;(\cos\theta)^{n-1} \tag{5}$$

for n = 1

$$f(\theta, 1, N) = \sin\theta\,(\cos^2\frac{\theta}{2})^{N-1} \tag{6}$$

and for n = N

$$f(\theta, N, N) = \sin\theta\,(\cos\theta)^{N-1} \tag{7}$$

The maximum amplitude of the echo due to the first pulse is given by solving

$$\frac{\delta f(\theta, 1, N)}{\theta} = 0 \qquad \text{One finds:} \quad \sin\theta = \frac{1}{\sqrt{N}}$$

and

$$f_1(\sin^{-1}\frac{1}{\sqrt{N}}, 1, N) = \frac{1}{(eN)^{\frac{1}{2}}}$$

$$f_N(\sin^{-1}\frac{1}{\sqrt{N}}, N, N) = \frac{e^{\frac{1}{4}}}{(eN)^{\frac{1}{2}}}$$

Note that

$$f_N/f_1 = e^{\frac{1}{4}} > 1$$

f_1 is than the smaller signal.

We may assume a decay factor due to loss of spin phase memory of the form e^{-t/T_2} where t is the time between first pulse in and last pulse out. We then require, for a system with magnetization, $\bar{M}$,

$$P_r(\bar{M})\, f_1^2\, e^{-t/T_2} \geq \alpha S$$

where S is the threshold system sensitivity

α = required signal/noise ratio

now we may replace t by $2Nt\omega$, where $t\omega$ = bit duration, and bit spacing and N = total number of pulses.

We then determine the capacity N from

$$\frac{P_r(\bar{M})}{eN}\, e^{-\frac{2Nt\omega}{T_2}} \geq \alpha S$$

Typical numbers:

$P_r \sim 50 \times 10^{-3}$ watts (helix with $M \sim 10^{-3}$ c.g.s. $V_s \sim 0.01\ cm^3$)

$t\omega \sim 10^{-8}$ secs.

$T_2 \sim 2 \times 10^{-6}$ secs.

$S = 80$ dbm $\sim 10^{-11}$ watts

$\alpha = 100$

Solve for N

$$\frac{50 \times 10^{-3}}{eN} \quad e^{-10^{-2}N} \quad \geq \quad 10^{-9}$$

$$\frac{e^{-10^{-2N}}}{N} \sim \frac{e}{50} \quad 10^{-6}$$

$$\sim .05 \times 10^{-6} \sim 5 \times 10^{-8}$$

compatible with bandwidth of $\sim$100 Mcs.

This equality holds for $N \sim 1000$ bits. The total time involved is

$2 \times 1000 \times 10^{-8} \sim 20$ microseconds.

SECTION 4

SLOW WAVE STRUCTURES FOR SPIN ECHO MODULE (SEM), (REF. III)

A great deal has been written about slow wave structures for TW tubes which will be reviewed for perspective. The slow wave transmission lines used here are of interest because

$$\frac{W}{P} = \frac{1}{v_g} \qquad (1)$$

where W is the stored energy in either the electric or magnetic field, P is the transmitted power, and v_g is the group velocity measured axially. This means that the lower the group velocity, the higher the stored energy per unit power transmitted. While TW structures can be used for the purpose at hand, they are not necessarily optimum for the purpose at hand for two reasons: (a) They are designed to give the desired phase velocity (usually in the range of $\frac{c}{16} < v_p < \frac{c}{3}$ where c is the velocity of light, i.e., 1000 < volts < 30,000) rather than a low group velocity and (b) they are designed to give a maximum electric field along the axis whereas the present application indicates a maximum magnetic field.

A comment reviewing the relationship between phase and group velocity may be helpful (see Ref. 5). All traveling wave structures have velocity characteristics which can be described in terms of the phase shift of a wave per unit length, β, as a function of frequency, $\omega = 2\pi f$.

Phase velocity is then given by

$$v_p = \omega/\beta \qquad (2)$$

and group velocity is given by

$$v_g = d\omega/d\beta \qquad (3)$$

as in ordinary transmission line theory. Each component is thus seen to be a function of frequency. If one is known, then the other can be determined by

means of such relations as

$$v_g = \frac{v_p}{1 - \frac{\omega}{v_p}\frac{d\,v_p}{d\,\omega}} \qquad (4)$$

As an example of the relationship between the various representations, the velocity frequency curves of a simple helix are shown in Fig. 6. Fig. 6a shows phase velocity equal to the velocity of light at very low frequencies and dropping to a low constant value in the working range. Asymptotic velocity is relatively independent of outer conductor diam. provided only it is not too close to the inner conductor (see Ref. 6). Neglected in this figure are certain "forbidden" bands (see Refs. 5 and 7). Actually, the helix is a multi-stop-band filter with stop-bands centered about the frequencies at which the helix length per turn is equal to an integral number of half wavelengths. At such frequencies, the helix may radiate, or if enclosed, will not transmit energy. From Fig. 6a and Eq. (2), Fig. 6b is readily obtained. This looks something like the phase shift characteristic of a low pass filter with a zero pass band. Fig. 6b is usually plotted with the axes reversed as shown in Fig. 6c. The reason for this is that the phase velocity at point "1" is simply the slope of a line through it and the origin while the group velocity is the slope of a tangent to the curve at point "1". From Fig. 6c and Eq. (3) the group velocity as a function of frequency is expected to look like Fig. 6d. The above curves are for the fundamental mode only which are not the same as for the accompanying space harmonics to be discussed later.

Velocity characteristics of a transmission line with a periodic structure are somewhat different. As an example, consider the concentric line with the folded inner strip conductor shown in Fig. 7a. This is chosen because it resembles the cross- or contra-wound helix to be discussed later. The exact shape of the inner and outer conductors does not matter too much. It is apparent that the structure is a low pass filter with higher order pass bands. The stop bands occur when the distance between corresponding points along the inner conductor is an integral number of half wavelengths accordingly, the ω-β diagram has the form shown in Fig. 7b. Phase shift increases from zero at zero frequency to π radians per "fold" at the upper limit of the low pass band. It then remains constant through the first stop band. Phase shift then increases from π to 2π radians per "fold" in the next pass band, etc. The corresponding curve of phase velocity vs. frequency then has the

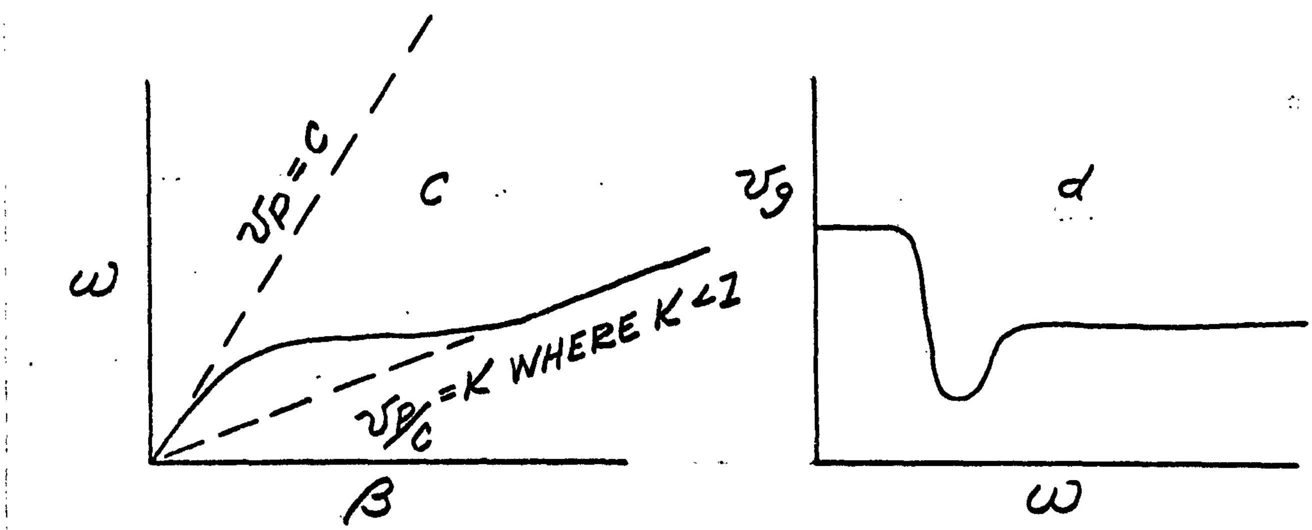


Figure 6

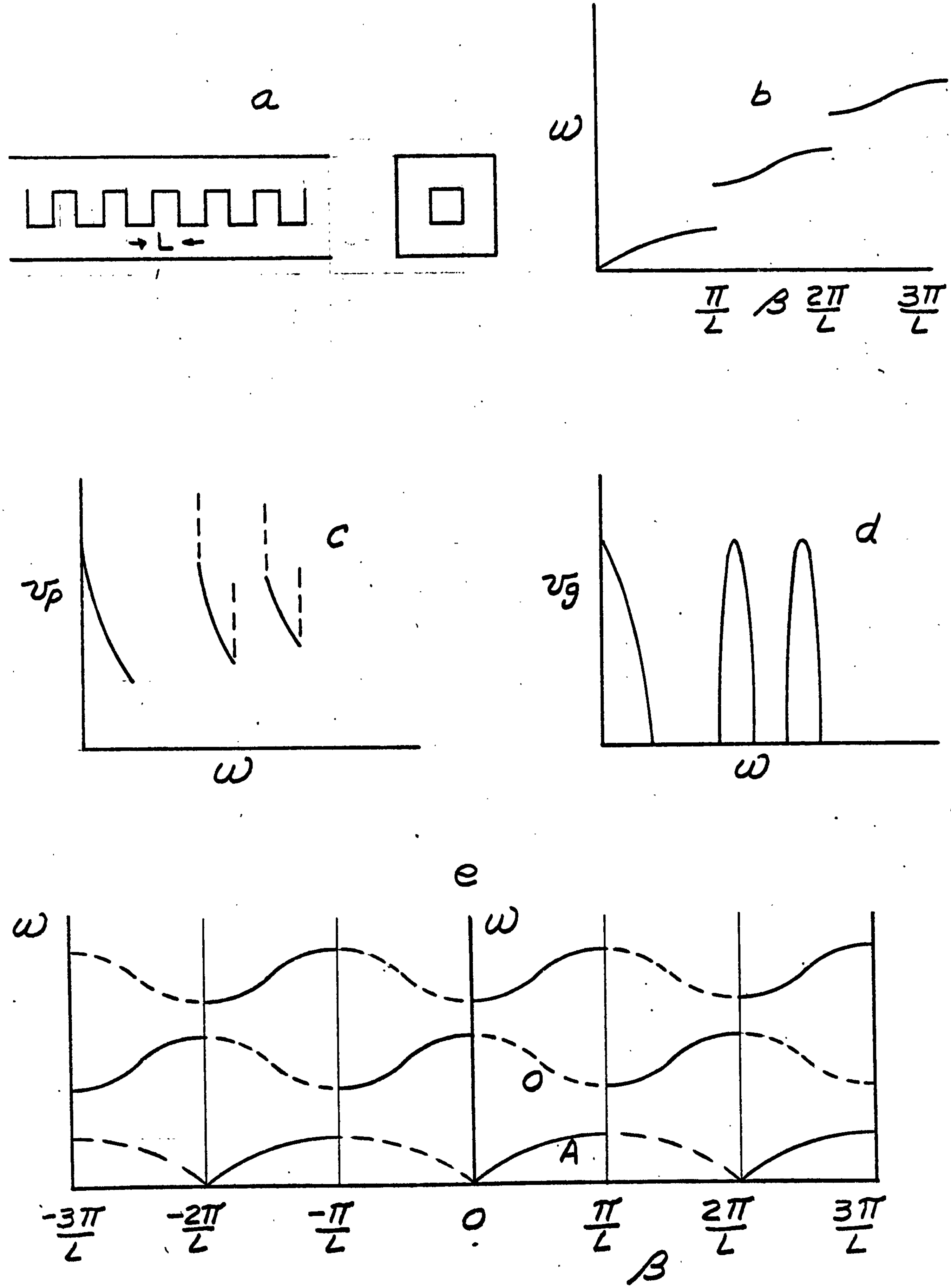


Figure 7

form shown in Fig. 7c where v_p is a decreasing function of frequency in each pass band and having at most a value determined by the center line foreshortening. Phase velocity is presumably infinite in the stop bands, but this is of no significance since attenuation is high and power transmission negligible. Group velocity vs. frequency has the interesting form shown in Fig. 7d, derived from the slope of the $\omega - \beta$ curve of Fig. 7b. This shows that the group velocity theoretically drops to zero at the band edges and is at most the velocity of light reduced by the center conductor "folding" factor. The scales of Figs. 7c and 7d are the same and the frequency scale is aligned for use of comparison.

Dr. Dan Kaplan has suggested that the fundamental asymmetric mode of the contra-wound helix might be good for the stated purpose. This is a very astute observation which would escape most people. It appears to have a great deal of promise but also some possible problems which will now be briefly discussed. First consider the simple single helix which has been tried and found to work. Here the paramagnetic material is placed inside the helix which forms the inner conductor of a concentric line. The simple helix is extensively used for TW tubes where it is useful because it develops a strong axial electric field. The magnetic field is strong and non-uniform close to the wires so the ideal core would be a close fitting hollow cylinder close to the helix yet fitting inside of it. Kaplan has reported that the attenuation of the helix does not go down as temperature is lowered, which is surprising and which is difficult to understand. Although the simple helix works, it can surely be improved upon.

Before discussing the contra-wound helix, it will be helpful to review two other concepts, namely "impedance" and "space harmonics." When one sees the term "impedance" in papers about TW tubes, it is well to remember that the writer is <u>usually</u> talking about a high frequency equivalent "interaction" impedance. This relates the axial electric field with which the beam interacts to the transmitted power. It is usually defined as

$$Z_i = \frac{E_z^{\,2}}{\beta^2 P} \text{ ohms} \qquad (5)$$

where Z_i is the "interaction" impedance to rf in ohms

E_z is peak axial electric field in volts

β is phase factor in radians per unit axial length

P = transmitted power in watts

Note that all factors are functions of frequency. Note, also, that the factor 2 has been omitted in the denominator - an historical accident perpetrated by J. R. Pierce. The factor β^2 appears in the denominator since it is involved in electron interactions. It has a value of unity somewhere near the middle of each pass band, but may vary from 0 to π near band edges.

In contrast, the usual circuit impedance is given by

$$Z_c = \frac{E_r^2}{2P} \quad \text{ohms}$$

where Z_c is "circuit" impedance in ohms

E_r is a mean value of radial electric field somewhere between inner and outer conductor in volts per unit length

P is power transmitted in watts. Z_b and Z_c may have about the same value at pass band interiors, but may differ widely near band edges. Z_b can only be measured by the behavior of an electron beam, whereas Z_c can be measured with a bridge or other circuit techniques.

The term "space harmonic" refers to the various solutions of the wave equation which are necessary to give a complete solution for all but very simple geometrical configurations. These are always encountered in the boundary value solutions of irregular structures and are commonly referred to as higher order modes. They have a special significance in the case of TW tubes because electron beams can interact with them individually. They are called space harmonics because they tend to have a spatial distribution relatively independent of frequency. If a structure has n turns or n teeth per inch, then there will be field components with n, 2n, 3n, etc. variations per inch. The space harmonics are strong near the wires or teeth and get weak fast away from them. Backward-wave oscillators use only a single space harmonic.

In addition, the space harmonics have velocity characteristics which are different from those of the fundamental mode. This is evident if we extend the curves of Fig. 7b as shown in Fig. 7c. The extensions represent the addition of space har-

monics (Refs. 5 and 8). The complete diagram is essentially the same as that of a uniform continuous string or a one-dimensional lattice of polyatomic molecules (Ref. 8, pp. 65-68 and Fig. 17.2). Fig. 7c is drawn in alignment with Fig. 7b for comparison. Shown are the first three pass bands only. Beam electrons may interact with any part of these curves. In fact, a beam of a given velocity may react with several parts of these curves at once as given by the interaction of a line through the origin with a slope corresponding to a given velocity with the various branches of the curves. All portions of the curves to the right of the origin have a positive phase velocity. Those portions to the left of the origin have a negative phase velocity. Shown solid are those parts of the curves which have a positive group velocity (slope). Shown dotted are those parts of the curves which have a negative group velocity. It is apparent that any combination of $\pm v_g$ is possible. The TW amplifier operates on segments such as A of Fig. 7c which has both a positive phase velocity and a positive group velocity; i.e., the electron beam and the energy move in the same direction. On the other hand, the backward-wave oscillator, (BWO) operates on segments such as O in Fig. 7c. Such segments have a positive phase velocity and a negative group velocity. The RF energy moves from collector to cathode, but it has a field component in the other direction with which the electron beam can interact.

The various segments of Fig. 7c can be correlated with corresponding $v_p - \omega$ curves of Fig. 9 of Ref. 9 remembering that this association applies to symmetric modes of the cross-wound helix only.

The cross-wound or contra-wound helix was developed to overcome some of the limitations of the simple unifilar helix for high voltage TW applications. Its conception and analysis by Chodorow is a brilliant piece of work (Ref. 10). These limitations were (1) the electron interaction impedance is reduced at high voltages for fundamental mode operation because of the high electric energy of the higher order modes and (2) the high electron interaction impedance of some space harmonics can result in backward wave oscillation. The cross-wound helix is a twin helix with one wound upon the other in the opposite direction. Electrical contact at the crossover points is assumed to exist. This gets hard to draw, but is attempted in Fig. 8a with the top side shown solid and the bottom shown dotted.

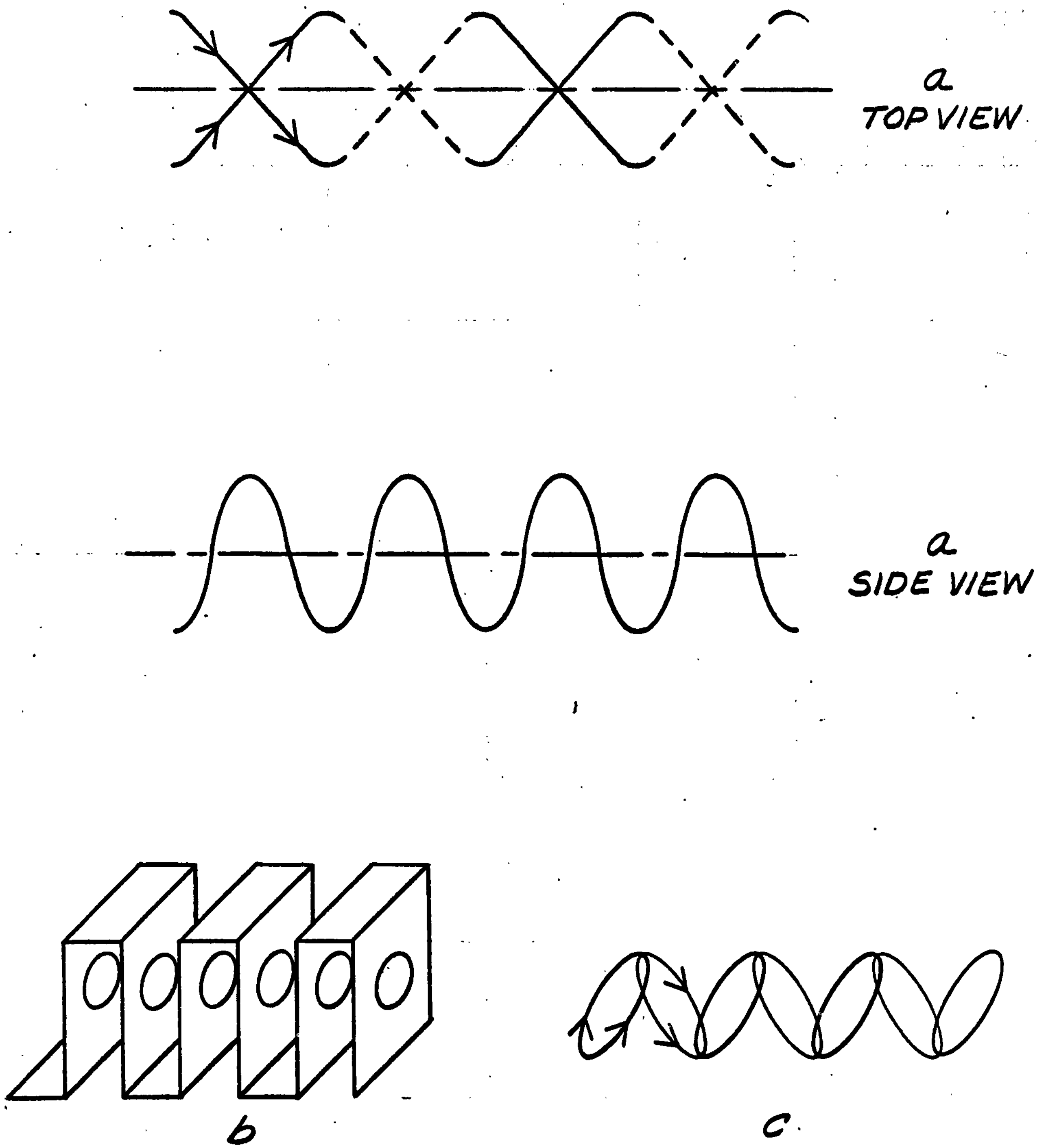


Figure 8

The relation between the structure of Fig. 7a and the cross-wound helix becomes apparent if one makes a series of holes for the passage of an electron beam as shown in Fig. 8b. Shown in Fig. 8c is a corresponding view of the cross-wound helix. The arrows show the direction of current flow in the first pass band of the symmetric helix. It is seen that the axial magnetic field components are cancelled which is ideal for TW amplifier because the axial field is then purely electric. The magnetic field has to be somewhere and is strong close to the wires in the space harmonics while the electric space harmonic fields tend to be weak.

Antisymmetric (a.s.) fields can exist on the same structure, but have different properties. The a.s. fields are similar to those on a two wire transmission line with periodic shorts between the lines as shown in Fig. 9a. The relation between this and the cross-wound helix is seen if one folds the structure as shown in Fig. 9b which should be compared with Fig. 8c. Shown in Fig. 9a and 9b are currents in the lowest pass band which is expected to occur in the vicinity of frequencies for which the line segments are an integral number of half wavelengths or the integral circumference of the cross-wound helix is an integral number of full wavelengths. Reference to Fig. 9 of Ref. 6 shows this to be the case. It is seen that for the fundamental a.s. mode this is indeed the case. A rather large structure would result for the present application, namely a helix about 1cm, in diameter at X-band. It can be shown that the axial electric field is zero for the desired mode which makes it ideal for the intended application. Size could be reduced about 20 percent from the curve of Fig. 9, Ref. 6.

Accordingly, the $\omega - \beta$ diagram of the a.s. modes has the form of Fig. 9. The group velocity as a function of frequency would then look like Fig. 9a with group velocity going to zero at the band edges. Nevin (Ref. 6) shows a fundamental mode with a bandwidth of about 35 percent.

The cross-wound helix is thus seen to have many of the desired properties though some aspects require further study. These are:

1. Optimum Frequency. Bandwidth is not a problem because the material used has a 1.5 percent bandwidth and the CWH has a 35 percent bandwidth. Although the

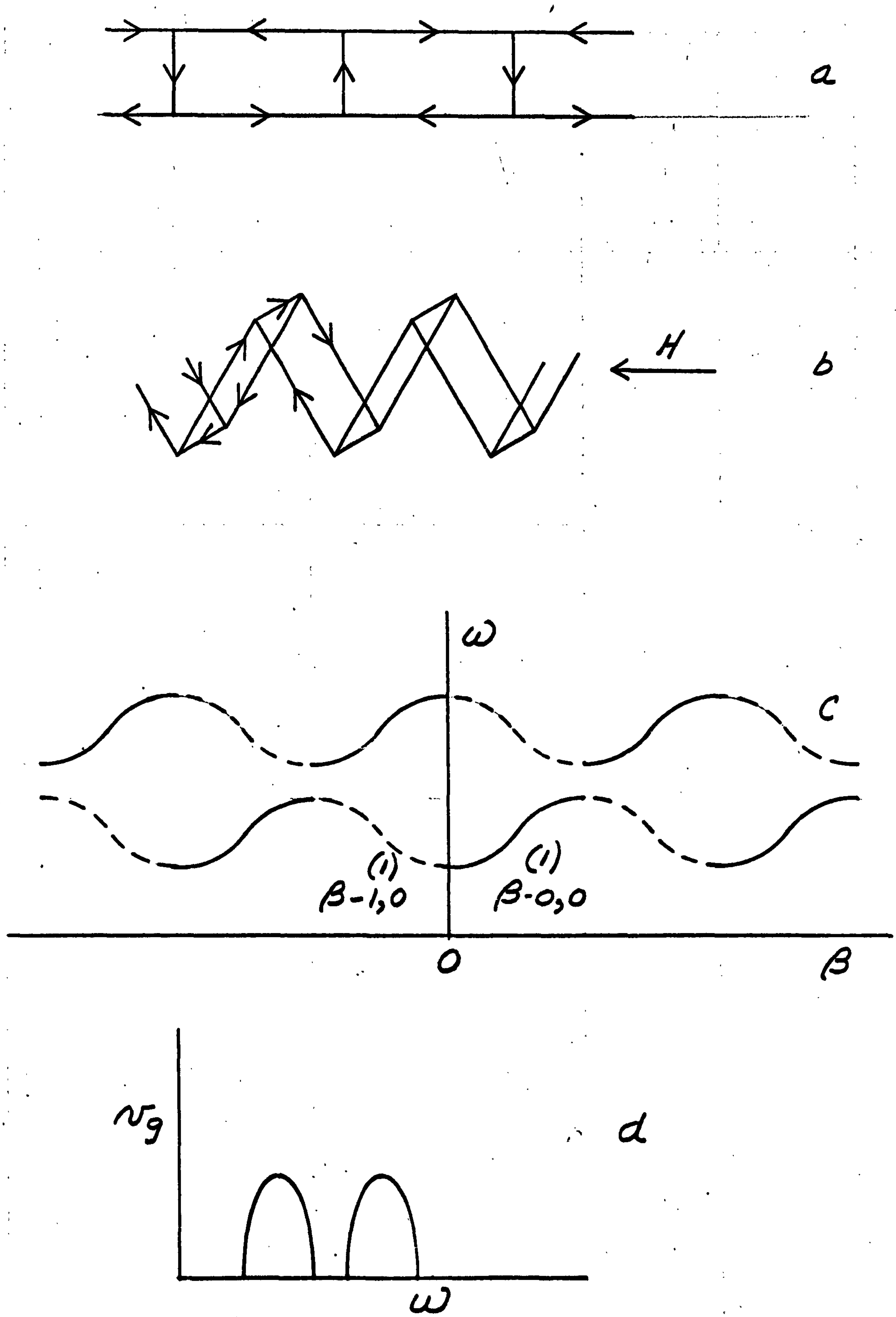


Figure 9

group velocity theoretically is zero at the band edges, operation is not necessarily optimum here because the fields may vanish here and because impedance matching is generally difficult.

2. Impedance Matching. The impedance of filters tends to be constant only at band centers and becomes either zero or infinite at band edges. However, a great deal of information is available on this subject. (Ref. 11, Vol. 2).

3. Termination. The termination of periodic structures is another impedance matching problem. With very small structures, various tapers can be used. It would be helpful to know the loss characteristics of the spin echo material as well as the dielectric constant and the effective permeability.

4. Size. This is a serious problem which would have to be studied. At this time it appears difficult to excite the desired mode in a structure the size of a simple helix.

5. Mode Excitation. The a.s. modes require a push-pull excitation. This could be achieved by an inductive loop coupling into a shorted end turn. It could also be done by cutting an end turn to get two terminals and then using a balun to convert from co-ax to two-wire form. The latter would be less simple, but the former might also excite the symmetric modes. Symmetric mode excitation means should be avoided.

This discussion really does no more than set the stage for further studies. It does begin to bring into focus the limitations and problems associated with the various approaches. A preliminary intuition is that the resonant simple helix would be best if its fields are suitable. It can be made very small. Impedance into a resonant section can be tuned with screw-type capacities. Bandwidth is probably adequate.

SECTION 5

POSSIBLE APPLICATIONS OF THE SPIN ECHO MODULE (SEM)

During the short duration of this limited study, it was not only not possible to exhaust and describe all the possible applications for the SEM, but some of the applications mentioned in this section might even be found less useful when exposed to further study and closer scrutiny. The few applications mentioned in this section will therefore have to be accepted as sample suggestions out of a possibly much larger reservoir of ideas.

5.1 The SEM as Wide Band Delay for Stored Reference Communications

A technique described in a four volume series of reports published by the Lockheed Missiles and Space Company under the title "Wide Band Carrier Communications" (LMSC Numbers 704011, 704016, 704047 and 6-90-61-59) seems to require the special qualities of the SEM.

This technique permits mixing intelligence with a wide band noise source, delaying this mixed signal by a controlled amount, and then adding it to the wide band source. Here, approximately 100 mc (presently available bandwidth of SEM) can be covered and the delay can be controlled precisely by the command pulse to the SEM for a time interval of 100 μs (either first pulse in-first pulse out or first pulse in-last pulse out).

As illustrated in Figure 10, the received wide band signal which contained the interspersed intelligence is detected by an inverse process of delaying part of the received signal mixing it with the other part. The exact delay is introduced by the SEM path before mixing to provide the reconstruction of the intelligence. The wide band carrier can be removed by a correlation process leaving the desired intelligence. This system could be implemented for a transmitted reference system as in Figure 10 or a stored reference system as illustrated in Figure 11. The important function performed by the SEM for this application is that inherent in its capability to delay wide band information. Clearly, it is a wide band variable delay line capable of delaying 100 mc information for 0-100 μs.

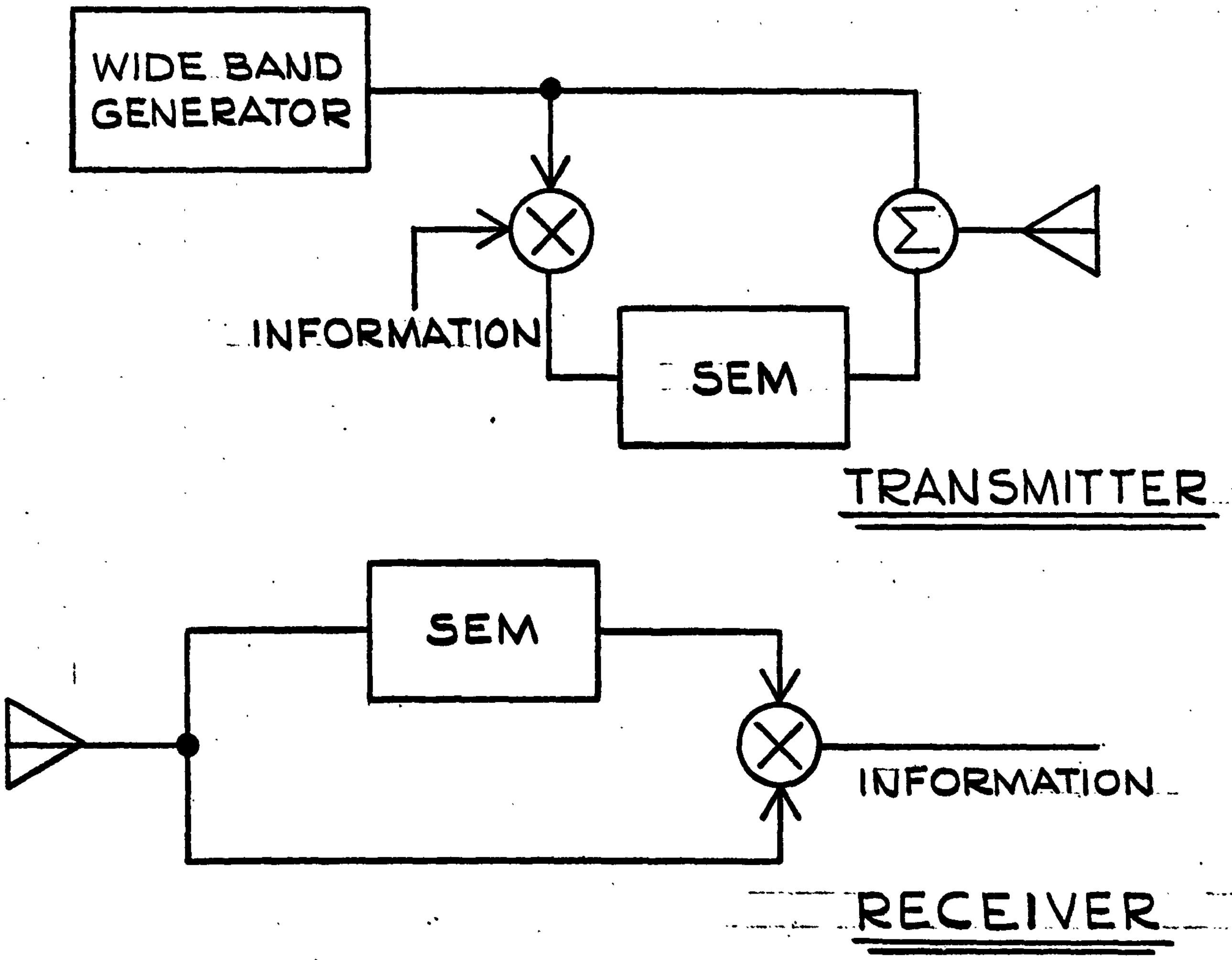

WIDE BAND
GENERATOR
INFORMATION
SEM
TRANSMITTER
SEM
INFORMATION
RECEIVER

Figure 10

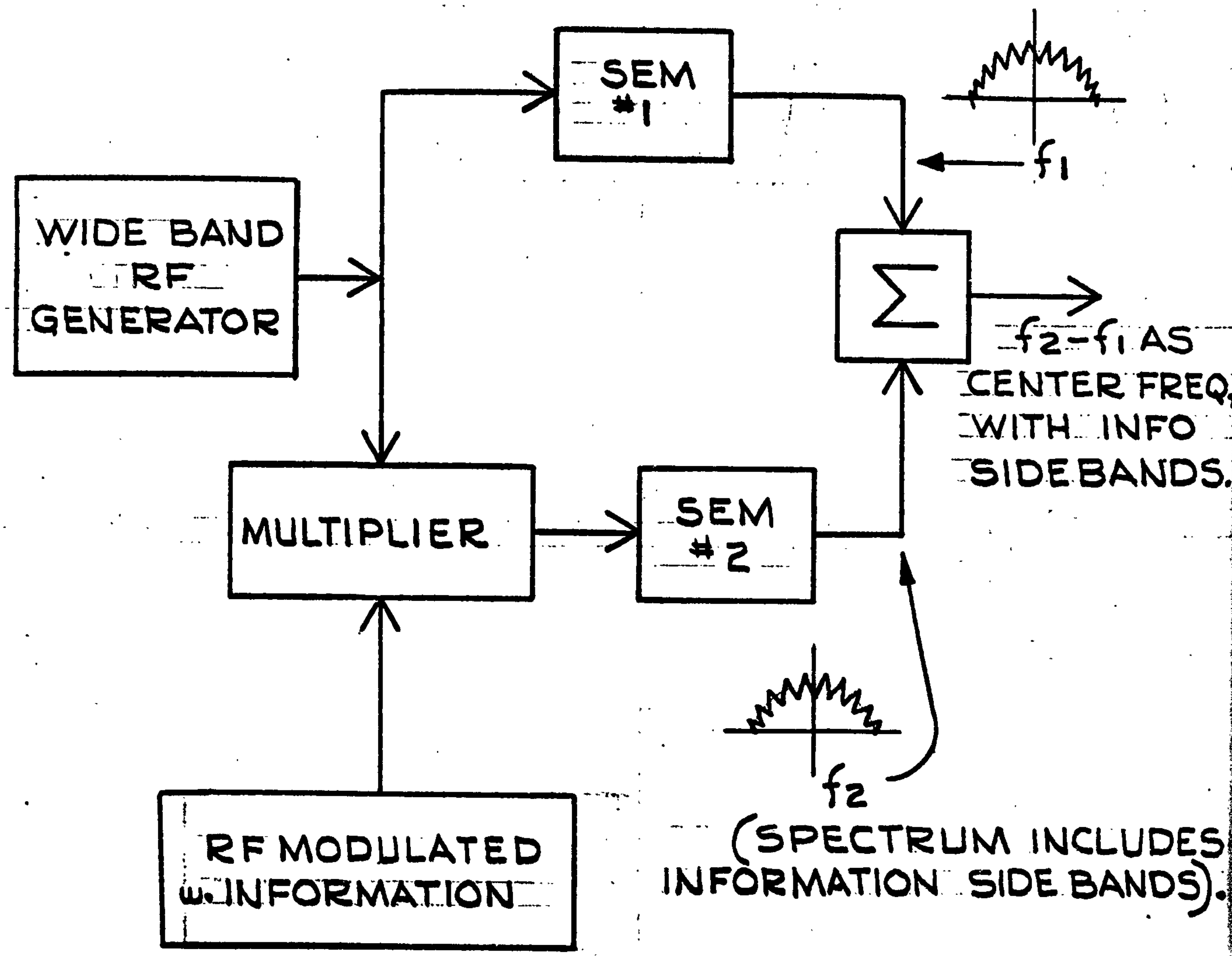

SEM
#1
f_1
WIDE BAND
RF
GENERATOR
Σ
$f_2 - f_1$ AS
CENTER FREQ.
WITH INFO
SIDE BANDS.
MULTIPLIER
SEM
#2
f_2
(SPECTRUM INCLUDES
INFORMATION SIDE BANDS).
RF MODULATED
w. INFORMATION

Figure 11

5.2 The SEM as Radar Repeater Jammer

The application of the SEM as a spoof generator or repeater jammer is quite straightforward. As illustrated in Figure 12, the enemy radar signal is received by the source being irradiated, any kind of a vehicle containing the SEM. The signal is then delayed by the SEM and returned by another transmitter. The returned SEM-delayed pulse can be increased in amplitude in order to overshadow the true radar reflection from the target. A small amount of delay would result in a composite signal which would distort the true range evaluation since the delayed signal can be made an order greater in magnitude. By varying the delay, the range can be made to appear greater or less than the true range would appear to the enemy. Using the second mode of operation of the SEM, a maximum delay of 100 μs is available for spoofing. This time delay can be thought of in terms of the range variation possible for confusing the enemy, and could result in range variations of approximately 45,000 feet. The delaying pulse can be modified to further confuse the receiver by changing the pulse shape and modulating it with noise. It is well to note that even a very narrow pulse received, as in high resolution radar, approximately 100 nanoseconds, can be modified without introducing pulse stretching as long as the bandwidth of the SEM is 100 mc. It appears that the SEM has both the desired bandwidth and the delay capability for such applications.

5.3 The SEM as Chirp Radar Detector

In the August 1963 issue of the Proceedings of the IEEE, a paper entitled "The Detection of Chirp Radar Signal by Means of Electron Spin Echos" is presented. Pulse compression rates, dealing with essentially single pulse, of the order of 1,000 to 1 appear feasible. The attainable time resolution is determined only by the width of the paramagnetic resonance line and the length of the received waveform is limited by the phase memory time of the spin pockets in the active material. This type of radar could be used to provide high range resolution for surveillance systems with all weather capability since this phenomenon is applicable to the S-band region.

5.4 The SEM as Coherent Delay Line

A natural application for the SEM is for a delay line where the information recall time can be accurately controlled. This has a number of applications

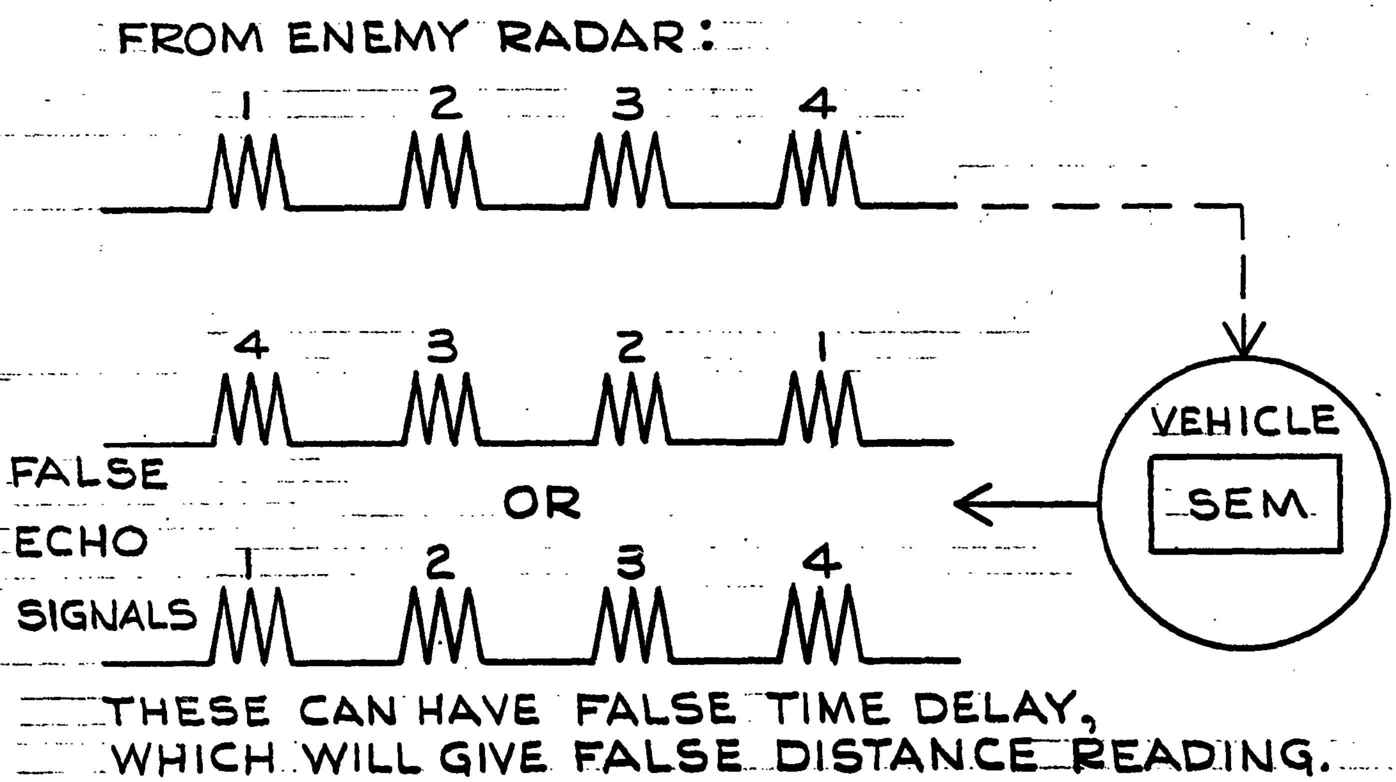

FROM ENEMY RADAR:
1
2
3
4
VEHICLE
SEM
4
3
2
1
FALSE
ECHO
SIGNALS
OR
1
2
3
4
THESE CAN HAVE FALSE TIME DELAY, WHICH WILL GIVE FALSE DISTANCE READING.

Figure 12

where coherence is required: coherent radar, range devices, etc. Although the shift register in a digital timing unit might have superior features, a trade-off appears possible for exact coherence, size, weight and complexity.

5.5 The SEM as Oscillator Control

It might be possible to use the SEM echos to stabilize the frequency of an oscillator. This could be achieved by storing either digital or analog pulses in one or more SEM crystals, using these to compare the output of an oscillator at time $t + \tau$, with the output at time t. This may be the only oscillator stabilized by remembering what it was doing τ seconds ago. The frequency of the memory feedback is a property only of the stability of the crystal lattice.

5.6 Application of the SEM as Computer Memory

This paragraph describes the results of a brief study to determine if the Spin Echo Module (SEM) can form the basis of a memory system competitive with existing memories. Particular emphasis was to be placed on looking for an application for the SEM in an existing computer system; for such an application, the SEM would have to demonstrate a marked advantage in taking over a conventional memory function from the memory system presently performing that function. An attempt to find and justify totally new memory functions would be a research effort in itself, and was not attempted here.

5.6.1 Analysis (Ref. IV)

The principal operational characteristics of the SEM in terms of the laboratory device constructed by Dan Kaplan are summarized in Table 1.

Table 1

Information Pulse Rate:	100 m.c.
Maximum Bit Storage:	500-600 bits
Permanence of Data:	volatile
Data Access Modes:	serial only with two modes: (1) first-in-first-out, and (2) first-in-last-out
Maximum Data Retention (Mode 1):	100 μs
(Mode 2):	5-6 μs

From an engineering standpoint, there are a number of additional characteristics of the SEM device which are important:

5.6.1.1 Negative Characteristics

a) The information must be stored in the form of a pulse modulated carrier (carrier frequency is 9.36-9.48 kmc) and hence microwave plumbing and switching, together with a microwave transmitter and receiver, are required components for the SEM.

b) The SEM is a one port structure. This means that a minimum of two SEM devices are required to construct a permanent memory system, and furthermore, the permanent memory capacity of such a system can only be half the volatile capacity.

c) The SEM device requires a cryogenic environment for its operation, and therefore, will normally be housed in a cryostat. Size, weight and servicing problems must be considered in relation to this environmental requirement.

5.6.1.2 Positive Characteristics

d) There is perfect retention of information pulse spacing (and thus pulse delay time) in the SEM. This feature eliminates one of the most serious difficulties attendant to the use of delay lines at high information rates.

e) The SEM requirement for an X-band carrier is a disadvantage when used with a conventional computer. This situation is reversed if the SEM were to be used in a microwave computer designed for X-band operation.

f) The storage medium of the SEM (as distinct from the overall memory package) is completely passive and should be very reliable.

g) The delay time of the SEM is electronically alterable, thus providing an additional measure of flexibility.

5.6.1.3 Logical Organization of a SEM Permanent Storage Unit - Comparison With Other Hardware

A specific configuration for a SEM (permanent) storage unit is presented in Figure 13 so that a basis will exist for further discussion and evaluation. The SEM(P) unit shown in Figure 13 represents a single serial-access memory channel. The laboratory cost of the above unit is approximately $10,000, and an estimated lower bound on the cost of a production unit is $1,000-$2,000 (assuming the cost of the transmitter and cryostat is apportioned over 10 or more similar memory units. This gives an estimated cost per bit of approximately $2-$4, for a production 500 bit capacity SEM(P) unit, at an average access time of 2.5 us.

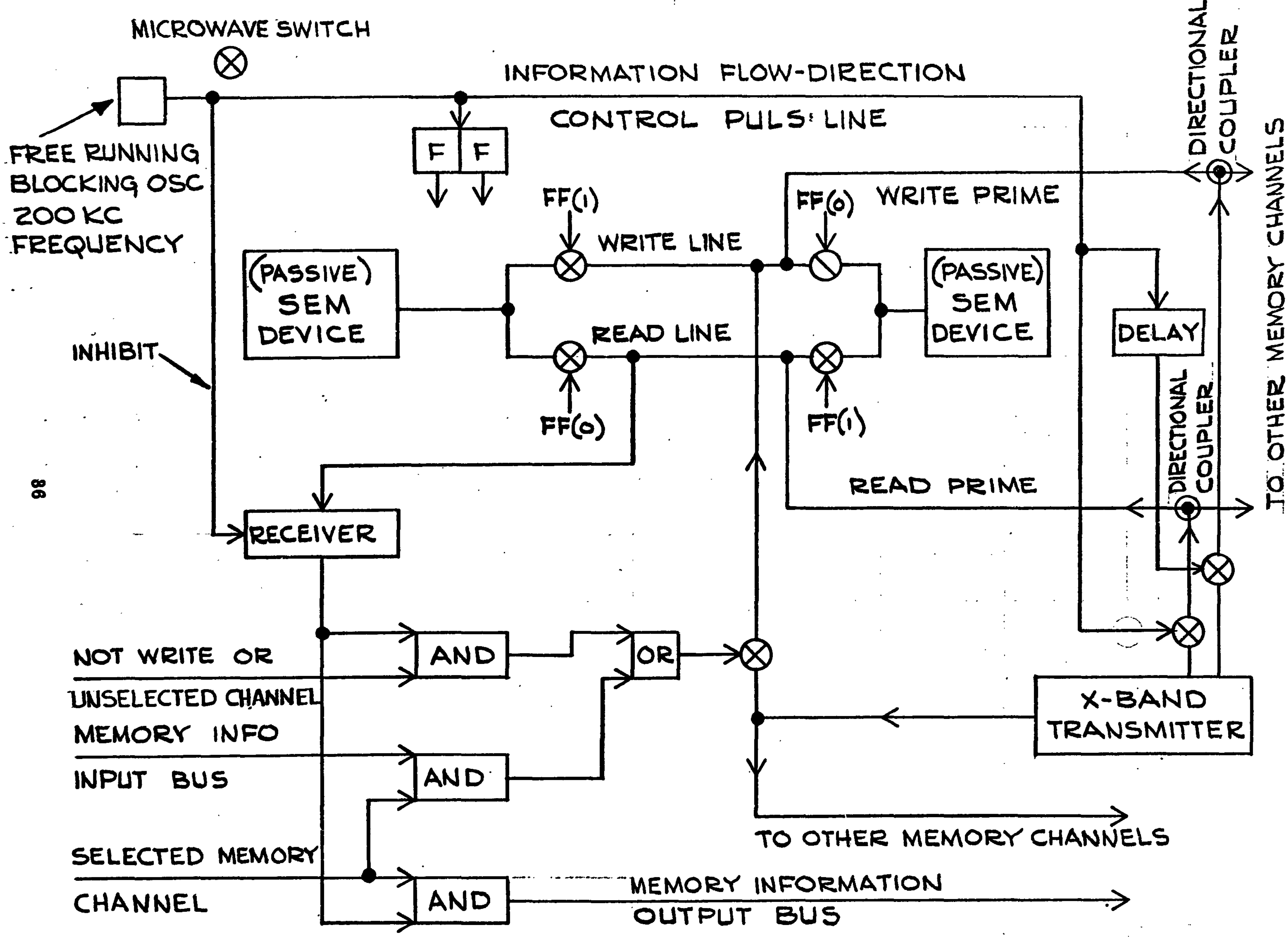

MICROWAVE SWITCH
INFORMATION FLOW-DIRECTION
CONTROL PULS LINE
FREE RUNNING
BLOCKING OSC
200 KC
FREQUENCY
F
F
FF(1)
WRITE LINE
FF(0)
WRITE PRIME
(PASSIVE)
SEM
DEVICE
READ LINE
(PASSIVE)
SEM
DEVICE
DELAY
INHIBIT
FF(0)
FF(1)
READ PRIME
DIRECTIONAL
COUPLER
DIRECTIONAL
COUPLER
TO OTHER MEMORY CHANNELS
RECEIVER
NOT WRITE OR
UNSELECTED CHANNEL
MEMORY INFO
INPUT BUS
SELECTED MEMORY
CHANNEL
AND
OR
AND
AND
X-BAND
TRANSMITTER
TO OTHER MEMORY CHANNELS
MEMORY INFORMATION
OUTPUT BUS

Figure 13

For memory application where random access is essential, the SEM(P) is not competitive with magnetic cores which currently cost between $.40-$1.00 per bit for .5 us random access time.

Where fixed sequence processing is the natural mode of operation, the 100 mc bit rate of the SEM(P) memory gives it a big speed advantage over the magnetic core (2 mc bit rate) and a cost advantage over fast access (.01-.1 us random access time) active memory elements such as the flip-flop. At present, the upper speed range of off-the-shelf flip-flops is a 10-20 mc bit rate at a cost of $40-$60 per bit. Experimental tunnel-diode flip-flops have been operated successfully at speeds of up to 200 mc and would probably cost between $50-$100 per bit.

There is a potential competitor for the SEM(P) in the glass acoustic delay line. Such delay lines are commercially available at 20 mc bit rates, have low temperature coefficients, and can store up to 4,000 bits. The cost of a 100-4000 bit capacity line, transmitter, and one receiver would probably be on the order of $500. Thus, while the absolute cost/bit is much lower here, the cost per bit for a given random access time is about the same as for the SEM(P). This type of memory also offers the possibility of inserting taps for higher access rates (at proportionally increased costs for the additional electronics). However, the SEM(P) still has the 5:1 speed advantage for fixed serial processing applications, and also has an advantage in terms of the synchronization problem.

5.6.1.4 Memory Requirements for General Purpose Digital Machines

Almost all of the large present day (commercially available) general purpose digital computers are parallel word organized machines; that is, the fundamental unit of information is a fixed length sequence of binary digits (bits) called a word, and this word is transferred as a unit along parallel data channels. Arithmetic and logical operations are also carried out in parallel in that all bits of a data word (of at least one of the operands) are processed simultaneously and in an identical manner. While word size is not a standardized item, most of the large machines have a word size of from 36 to 50 bits.

Memory requirements for the large G.P. digital machine are quite varied. Table 2 presents a summary of conventional memory functions.

If the SEM(P) capability is to be demonstrated by having it assume one of the computer memory functions (listed in Table 2), it will either have to be capable of permitting an increase in computer computation rate, or allow a cost reduction for the same computational capability.

Two factors are serious drawbacks in any attempt to demonstrate the SEM(P) as part of an existing G.P. machine. First, most of the memory functions (see Table 2) require random access to the data, and the SEM(P) is not competitive in cost or speed with the magnetic core for such applications. Second, the circuitry which performs the logic and control functions in the existing G.P. machines is matched in speed to the existing memory systems. If we replace one of the old memory systems with memory capable of operating at a higher speed, in most cases the logic circuitry would also have to be changed to take advantage of this higher speed capability; this would be equivalent to rebuilding a good part of the computer.

Of the various memory functions listed in Table 2, the only function worth considering for mechanization with a SEM(P) is the "associative store". Although no existing large scale computer has such a memory capability, many research papers have been written discussing its advantages. Until quite recently, the construction of an associative memory operating at a speed comparable to the main store, was not possible at a reasonable cost. While the exact dollar value of such a memory is still difficult to assess, there seems to be little doubt that the associative memory will be a part of future computer systems. An associative memory is commercially available from Goodyear which can locate and access data in 7 μs. The cost per bit for such a memory would probably run around \$5-\$8.

A SEM(P) associative store for a large scale G.P. machine would principally contain (approximately) 40 SEM(P) memory channels, a tunnel diode flip-flop register of 40 bit capacity, a high speed clock, and perhaps 80 tunnel diode logic gates. The average time to locate and access data would be less than 2.5 μs. Assuming a cost of \$2000 per 500 bit SEM(P) channel, \$80 per bit of tunnel diode memory, and \$40 per tunnel diode logic gate, the 20,000 bit memory system would cost approximately \$90,000, giving a cost per bit of \$4.50.

TABLE 2 (these comments pertain mainly to machines costing over $500,000)

Memory Function	Descriptive Comments	Typical Capacity (words)	Typical Word Access or Cycle Time (μs)	Typical Mechanization	Example of Machine Using Such a Memory	Capacity in Bits	Access or Cycle Time	Typical Access Requirement
1. Main Internal memory storage	-	4K-64K	.5-6	magnetic core	Philco 2000	$3x10^6$	1	Random
2. Large External Back-up Storage	-	10^7	10^5	magnetic disc	Philco 2000	10^8	$1.4x10^5$	Random or Sequential
3. Scratchpad	Relatively small high speed memory for use with subroutines	10^2-10^3	.5	magnetic core or thin film	Univac 1107	$5x10^3$	.6	Random
4. Buffer	Many such registers are normally used in all large machines	1	.2	Flip-Flop	Univac 1107	36	-	Random
5. Computing Registers	Accumulators and shifting registers	1-2	.2	Flip-Flop	IBM 7090	36-38	-	Random
6. Control Registers and Counters	Instruction registers, Index registers, Memory Address Registers	1 word or less	.2	Flip-Flop	IBM 7090	1-36	-	Random
7. Push down Store	Last-in-First-out Sequential Store	Any portion of main internal memory	.5-6	magnetic core	Burroughs B5000	$2x10^5$	6	Sequential
8. Associative Store	Content rather than location is used for address. This is actually a combined memory-computing function	-	-	Multiaperture magnetic structure or cryotron	Not incorporated in any existing machine. Such a memory unit is offered commercially by Goodyear Aircraft Co.	10^5 word lengths of up to 200 bit are acceptable	5	-

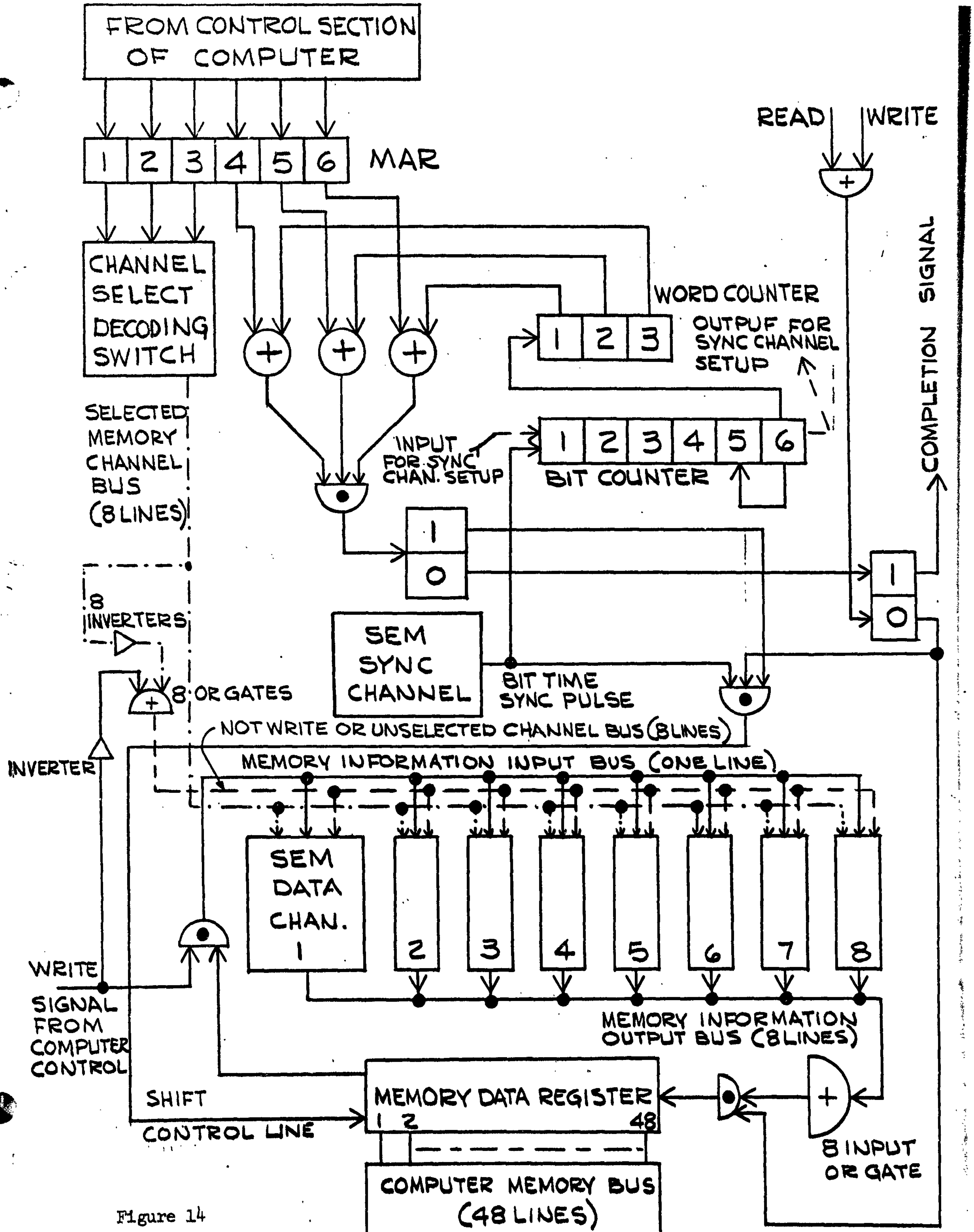
The SEM(P) associative memory system would operate by circulating its entire contents through the tunnel diode F.F. register once every 5 μs. Comparison between the associative memory contents and a key word stored in a computer register can be accomplished by high-speed tunnel diode logic. When a match occurs, the word in question can be read from the tunnel diode register into the computer, or a marker can be entered into a marker channel of the associative memory and the word read out on a later pass through the tunnel diode register if this is desired.

Figure 14 shows a block diagram for a memory to be used in connection with computers such as CDC 1604, Burroughs B5000, Honeywell 400 and 800, and Philco 2000.

The memory contains 64 words at 48 bits each with a memory cycle time of approximately 5 us. The following equipment would be necessary for this memory:

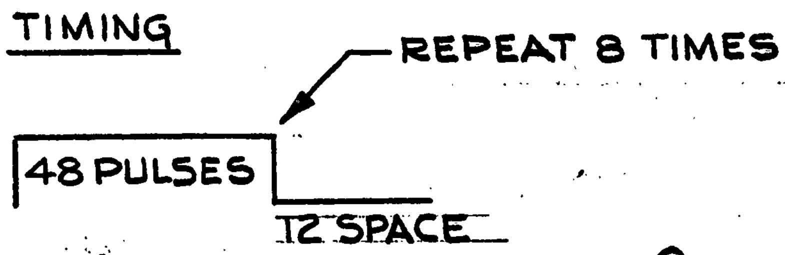
1 cryostat
8 SEM data memory channels (8 words each)
1 sync channel
3 multivibrators (two free-running and one monostable)
1 microwave transmitter
1 memory address register of six flip-flops (normal)
1 memory data shifting register of 48 flip-flops (fast)
1 bit counter of six flip-flops (fast)
1 word counter of three flip-flops (fast)
1 comparison register of three two-input AND gates (fast)
1 channel select decoding switch (normal)
9 inverters
3 control flip-flops (fast)
40 (approximately) tunnel diodes for gating

Figure 15a illustrates one of the eight timing pulses and Figure 15b illustrates a possible sync channel, the input of which comes from a free-running 200 kc BO, and its output is injected to the bit counter as indicated in Figure 14. This might be necessary since the timing information must be written into the SEM sync channel when the memory is first turned on.

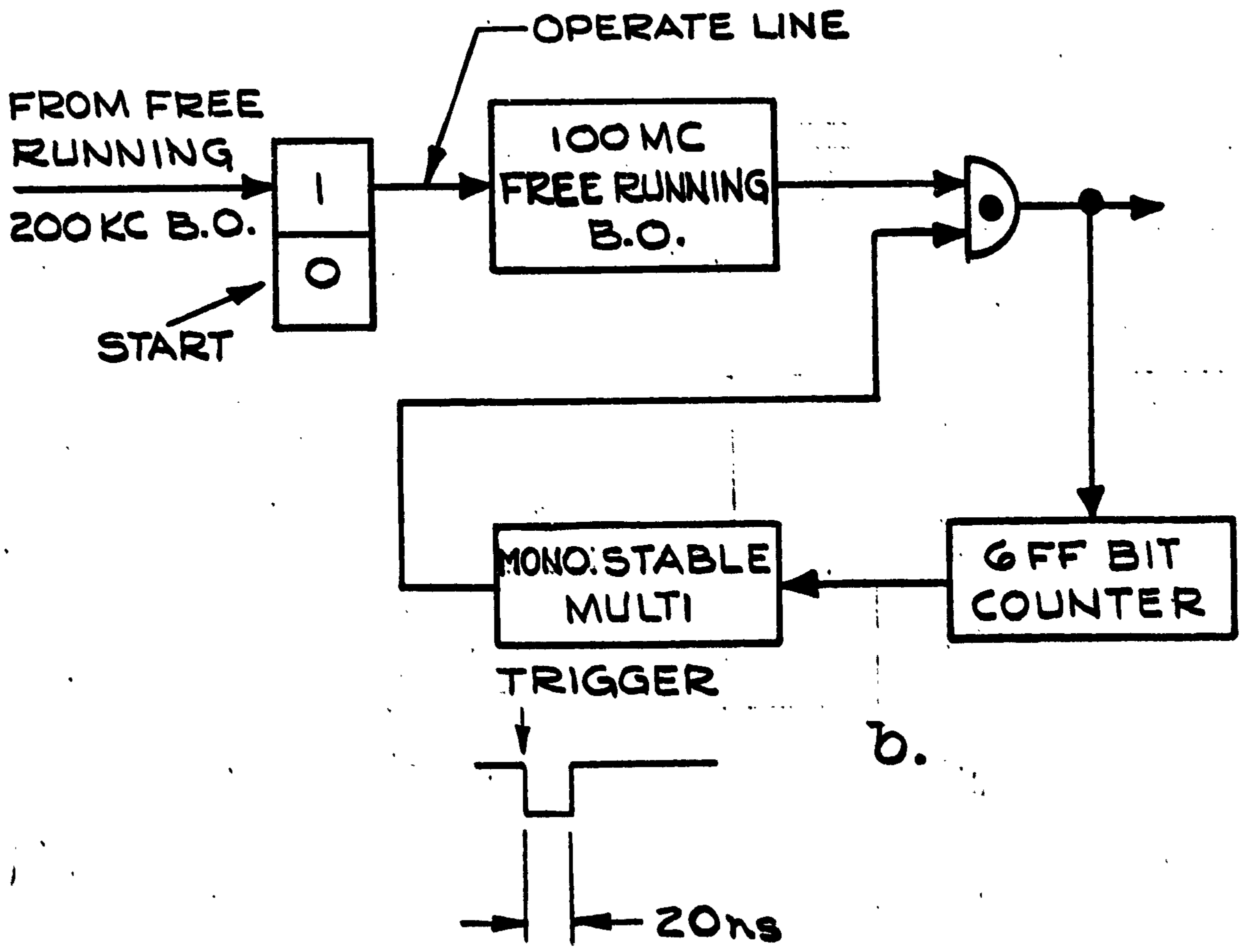


FROM CONTROL SECTION OF COMPUTER
MAR
1 2 3 4 5 6
READ
WRITE
CHANNEL SELECT DECODING SWITCH
WORD COUNTER
1 2 3
OUTPUF FOR SYNC CHANNEL SETUP
COMPLETION SIGNAL
SELECTED MEMORY CHANNEL BUS (8 LINES)
INPUT FOR SYNC CHAN. SETUP
BIT COUNTER
1 2 3 4 5 6
8 INVERTERS
SEM SYNC CHANNEL
BIT TIME SYNC PULSE
8 OR GATES
NOT WRITE OR UNSELECTED CHANNEL BUS (8 LINES)
INVERTER
MEMORY INFORMATION INPUT BUS (ONE LINE)
SEM DATA CHAN. 1
2
3
4
5
6
7
8
WRITE SIGNAL FROM COMPUTER CONTROL
MEMORY INFORMATION OUTPUT BUS (8 LINES)
SHIFT CONTROL LINE
MEMORY DATA REGISTER
1 2
48
8 INPUT OR GATE
COMPUTER MEMORY BUS (48 LINES)

Figure 14


TIMING
REPEAT 8 TIMES
48 PULSES
12 SPACE

a.


OPERATE LINE
FROM FREE RUNNING 200 KC B.O.
1
0
START
100 MC FREE RUNNING B.O.
MONO:STABLE MULTI
6 FF BIT COUNTER
TRIGGER
20ns

b.

Figure 15

5.6.1.5 The Digital Differential Analyzer (DDA) as a Vehicle for the SEM(P)

The DDA is a digital machine (containing a memory and switching circuits) which processes all data in quantized binary form. It differs from the G.P. machines in that it is designed specifically for the solution of ordinary differential equations or sets of such equations. This restriction upon its capabilities permits a great reduction in the amount of hardware needed to implement the machine.

The programming and functional operation of the DDA is very similar to that of the analog computer. Closed loop methods are used to solve differential equations by integrating a variable several times and then feeding this integral quantity back to the input of the loop.

For a given cost, the DDA can outperform both analog and G.P. digital computers in solving differential equations. It retains the ease of programming and speed of solution common to the analog computer while offering the accuracy available only in digital machines. Principal applications of the DDA are in real time control systems, simulators, and scientific computation.

The DDA consists essentially of a collection of digital integrators which may be interconnected in any required manner. In a simultaneous DDA organization, each integrator has its own associated arithmetic unit which allows concurrent operation of all integrators. In a sequential DDA organization, there is a single arithmetic unit which services each integrator in turn. For the simultaneous DDA the iteration period is the time taken to perform one integration step, whereas for the sequential DDA the iteration period is the time taken to process all integrators in turn. DDA may be further subdivided into serial or parallel machines according to the way in which the arithmetic is performed.

During each iteration period, each integrator receives a primary incremental input, Δx, and a secondary incremental input Δy, and generates an incremental output Δz, which approximates ydx. The simplest implementation of an integrator requires two registers, a y-register and an R-register, and two adders. One adder maintains the current value of y in the y-register by summing the Δy increments into it; the other adds y into the R-register

when Δx is positive, and subtracts it when Δx is negative. A positive Δz increment is emitted whenever the R-register overflows, and a negative Δz when R goes below zero. The Δz output of one integrator may serve as the Δx or Δy input of another. Differential equations may then be solved by properly interconnecting a number of these integrators.

A step usually taken to further simplify the structure of the DDA is to constrain the increments (Δx, Δz) to the values 0, $\pm 2^{-k}$ (k is a scale factor and can be different for the different increments). Because of this constraint, the DDA integration process is basically that of counting, and the increments can be represented in a ternary number system (0, +, -).

A sequential DDA using SEM(P) registers and serial arithmetic would require 7 memory channels. One channel for the y-register, one channel for the R-register, two (address) channels to specify the interconnections, two short channels or flip-flop registers to hold the increments and their signs, and at least one timing channel. Such a minimal system would have a typical capacity of 20 integrators and a maximum accuracy of one part in 2^{25}. The machine would be capable of 200,000 iterations per second. It should be remembered, however, that such a machine would have to be completely built with experimental circuitry (high speed tunnel-diode circuits would be necessary for the logic and control functions). The equipment cost of such a system would probably run in the neighborhood of $35,000. Input-output capability, function generators, etc., would cause an increase in this estimate.

For comparison purposes, the Packard Bell TRICE System (simultaneous organization, serial arithmetic) is the largest most versatile DDA commercially available at present. The basic configuration of this system (Model TC 5036) has a capacity of the equivalent of 40 integrators; it is capable of 100,000 iterations per second at a maximum precision of 26 binary digits and sign. The cost of this system is approximately $100,000.

5.6.1.6 Conclusions

The spin echo module appears to offer the basis for a serial memory system which is superior to existing memories in certain specific areas of application.

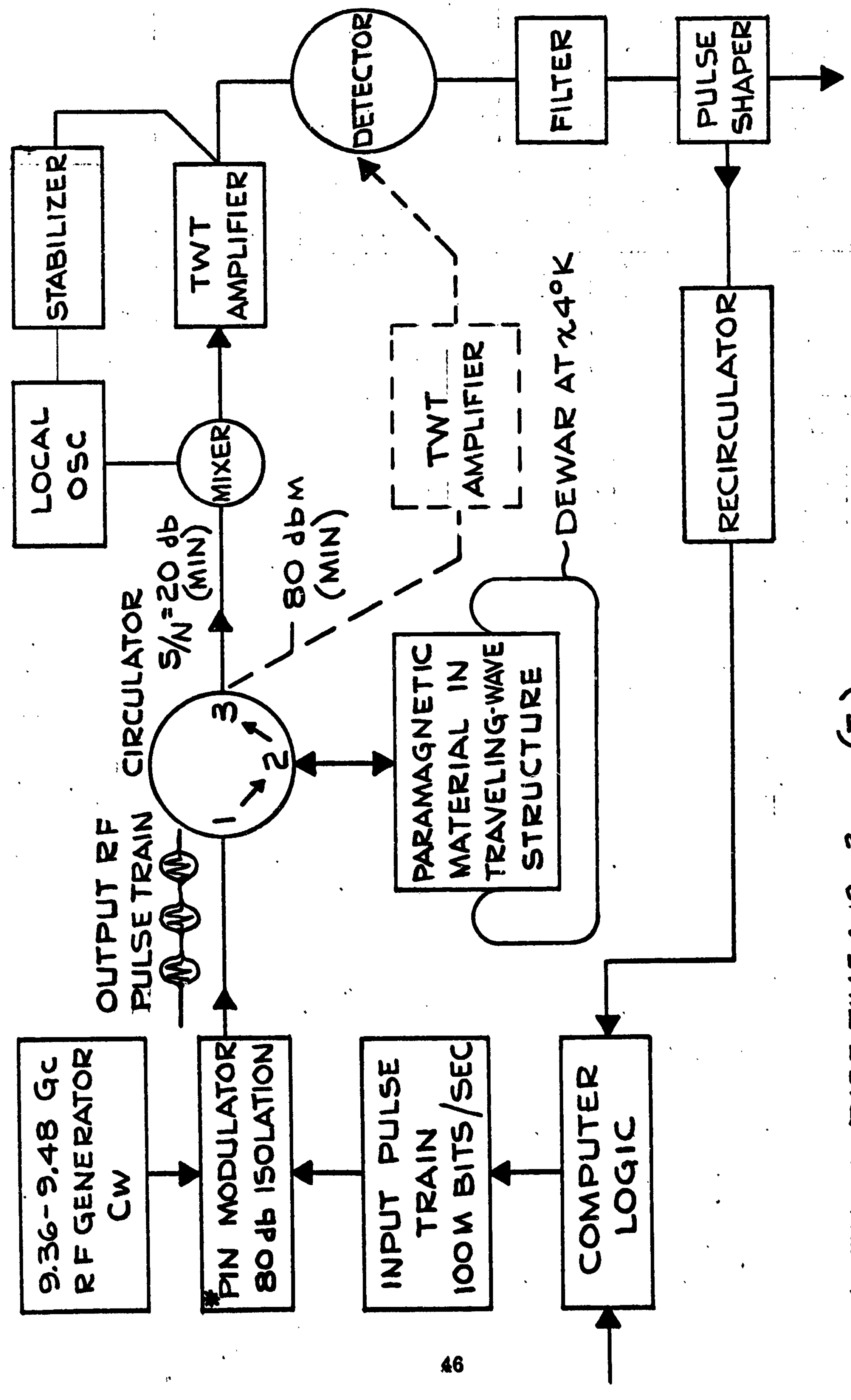
This superiority, however, is not great enough to permit order of magnitude improvements (in speed and/or cost) over competing systems already commercially available. This means that a convincing demonstration of the potential of the SEM(P) would have to involve a full scale system of commercial quality and usefulness.

The two applications for the SEM(P) suggested in this paragraph offer the possibility of satisfying the above criteria, but the following additional considerations now apply: In the case of the associative store, computer programs would have to be written to demonstrate the actual rather than potential usefulness of such a memory system. Thus, a programming effort would have to be undertaken along with an equipment development effort. In the case of the DDA, a commercially or scientifically useful system would require many pieces of auxiliary equipment in addition to an enlarged version of the basic system suggested. The total equipment cost for such an enlarged system would probably cost $100,000 or more and involve considerable product engineering effort.

5.6.2 The SEM Using PIN Modulator and Superhet for a Computer

To utilize the available bandwidth and delay of the SEM for a high capacity serial digital computer application requires RF signal conditioning before storage and high level detection after release (upon command) of RF pulses from storage. Figure 16 shows an SEM storage unit for a high capacity, high speed, computer which is capable of storing 100 Mega Bit pulse information in serial form. The sequence of operation would be as follows: The 100 MB serial pulse train from a preceding computer unit is fed to the computer logic stage which in turn feeds the logic modified 100MB pulse train to the PIN modulator. The PIN modulator pulse modulates the continuous wave RF carrier in accordance with the serial pulse information from the computer logic module. The PIN modulator is a solid state diode positioned in an X-band waveguide where a serial train bias pulse changes the guide impedance, thus reflecting the incident carrier. A number of such sections in series would provide the necessary 80 db isolation. A pulse modulated RF carrier is fed to a directional device (the circulator) from port one to port two which processes the pulse train to the SEM for storage. Approximately 1,000 bits of information can be stored by a quantum phenomenon dealing with the angular momenta of the material. The SEM for this case is a paramagnetic

SEM COMPUTER UNIT USING PIN MODULATOR & SUPERHETERODYNE RECEIVER



* PULSE RISE TIME : 2-3 ns (Tr)
PULSE FALL TIME : 2-3 ns (Tf)
POWER OUTPUT : 1 MW (Po)
ON-OFF RATIO : 80 db

Figure 16

material positioned in an X-band helix which is coupled to the circulator. To provide a recall pulse having a signal to noise ratio of 20 db, the input RF pulse power must be about 1 mw. This is an RF level which is easily obtained with standard commercial signal generators or can be easily generated with compact solid state RF generators. After detection, the recall serial pulse train is filtered and shaped. It may be necessary to feed back the information for continued storage via the recirculator. No pulse degradation is anticipated by this recirculation process since pulse shaping at an adequate signal to noise ratio is possible. The output pulse train can also be sent to the next logic unit.

Upon recall the RF serial pulse train is coupled to the helix output and then directionally fed from port two to port three. Since the signal level is below that required for a low level single ended crystal detector, a superheterodyne detection system is necessary. To provide frequency stability, a standard feedback is utilized to shift the local oscillator to maintain the intermediate frequency within the required limit. To provide the gain for envelop detection and to maintain the pulse shape fidelity, a wideband TWT amplifier is utilized.

The pertinent facts of the SEM computer storage unit described in this paragraph are summarized as follows:

1. Information rate - 100 MB
2. Storage time - 100 μs in mode #1 operation
   Storage time by recirculation should be several hours
3. Available bandwidth - 100 to 120 mc
4. Information format - serial pulse train
5. Pulse widths - 5 nanoseconds
6. Period (bit) - 10 nanoseconds
7. Pulse RF power required for SEM for a S/N of 20 db - approximately 1 mw
8. Isolation (on-off ratio of RF pulse) - 80 db.
9. Recall per cycle - 0 to 100 μs
10. Superheterodyne detection
11. Number of pulses stored - 400-1,000
12. Required cryostat - $4.2^{\circ}K$

5.6.3 Other Applications of the SEM in the Computer Field

One of the main implementation problems associated with the development of an SEM computer unit is that of generating the 10 nanosecond pulse train where the pulse width is 5 nanoseconds. Equally as important to prevent computer error generation is the requirement for an on-off RF pulse power ratio of 80 db. One example was described in the preceding paragraph, and three possible suggestions are presented in Figure 17a, b and c which should be capable of providing higher pulse power levels for application to the paramagnetic spin echo memory materials.

Miniature ceramic type voltage tuned magnetrons (Figure 17a) are available which have bandwidths in excess of 200 mc. The desired RF pulse train can be generated by the magnetron provided a fast pulse source capable of delivering 30-50 volts at a 100 MB rate can be developed. Modulation sensitivity is in the order of 2.5 mc per volt for voltage tuned wide band magnetrons.

Another similar scheme for developing the 100 MB pulse train is shown in Figure 17b using a backward wave oscillator (BWO). The BWO's are extremely wide band oscillators having excellent capabilities to generate nanosecond pulses. Once again, the main drawback is the absence of the high voltage pulse source with the required pulse rate capable of driving the BWO. Modulation sensitivities in the order of 2.5 mc per volt are found for the BWO's. Available information bandwidths in the gigacycles are common for BWO's, however, the RF output is not constant with frequency.

In Figure 17c a system using klystrons in a hybrid arrangement is illustrated which can provide high voltage RF pulses at 100 MB rate. Such systems require, however, considerable study since no reliable information is available on the actual on-off ratio of these pulse generation methods.

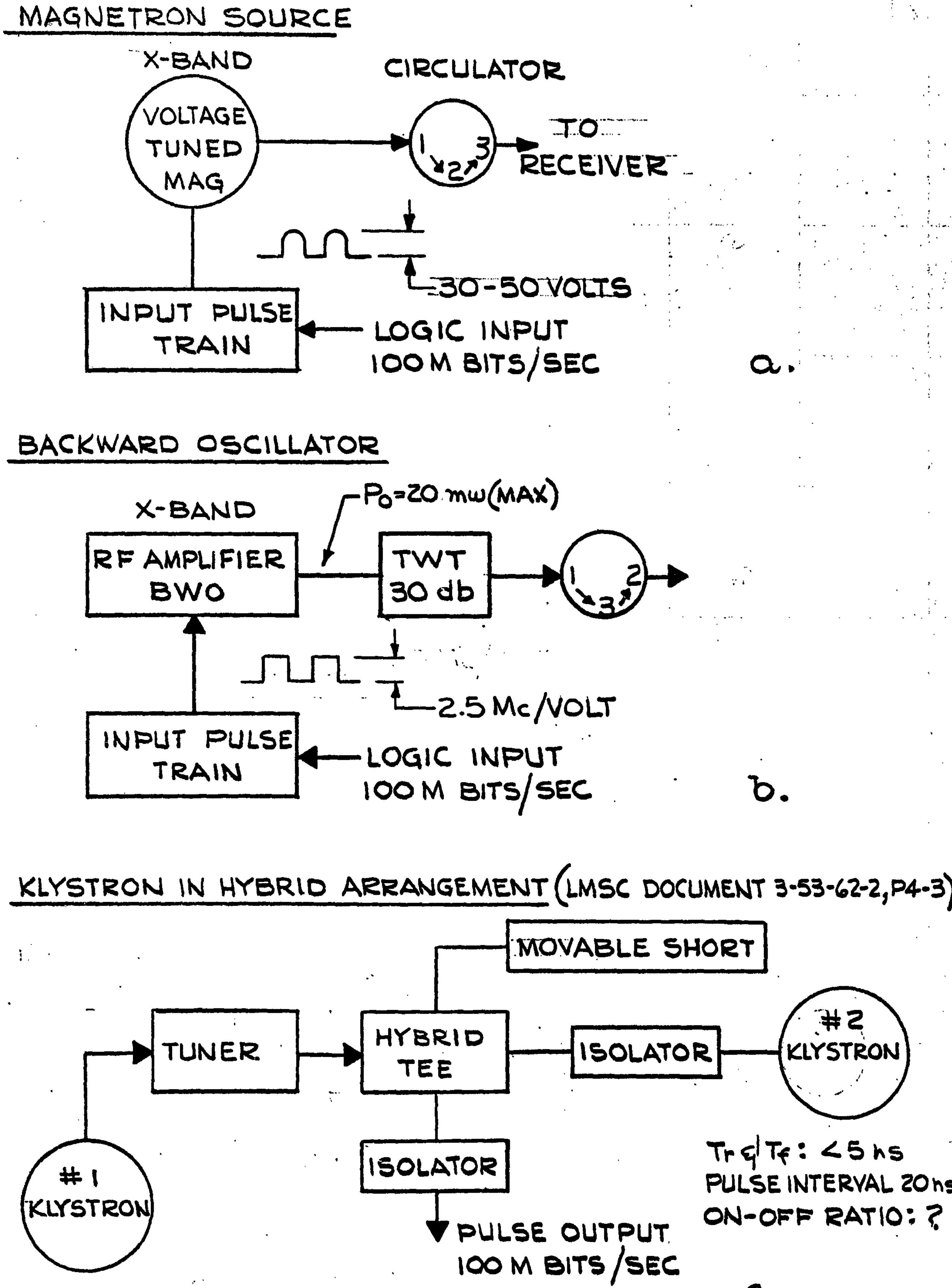

MAGNETRON SOURCE
X-BAND
VOLTAGE TUNED MAG
CIRCULATOR
1
2
3
TO RECEIVER
30-50 VOLTS
INPUT PULSE TRAIN
LOGIC INPUT
100 M BITS/SEC
a.
BACKWARD OSCILLATOR
X-BAND
P_0=20 mw(MAX)
RF AMPLIFIER BWO
TWT 30 db
1
3
2
2.5 Mc/VOLT
INPUT PULSE TRAIN
LOGIC INPUT
100 M BITS/SEC
b.
KLYSTRON IN HYBRID ARRANGEMENT (LMSC DOCUMENT 3-53-62-2, P4-3)
MOVABLE SHORT
TUNER
HYBRID TEE
ISOLATOR
#2 KLYSTRON
#1 KLYSTRON
ISOLATOR
PULSE OUTPUT
100 M BITS/SEC
Tr & Tf: <5 ns
PULSE INTERVAL 20 ns
ON-OFF RATIO: ?
c.

Figure 17

SECTION 6

ENGINEERING APPROACH

The preceding sections make the requirement for a concentrated effort in the area of application studies and engineering developments obvious. It appears that the suggested use of a helix in the SEM might yield excellent results without necessarily being the best configuration in which the SEM should be contained. Some alternate approaches should be examined, and if promising, developed. It might even be necessary to examine every one of the known microwave structures for this purpose. In addition to the suggestions of Section 4, 1 through 5, the following should be considered:

Linear Accelerator Structure. The present application does not require a low v_p like the TW tube. The apertured disc structure of the linear accelerator has $v_p = c$ but $v_g \ll c$. A difficulty is that it is rather large at X-band.

Comb-in-Wave Guide. This is like the Linear Acceleration Structure, but can be made much smaller. It would require WG to coax transitions.

Resonant Simple Helix. This might be the simplest and smallest after all. It should be possible to get the bandwidth. The magnetic field, however, is far from uniform and not very well concentrated.

Cavity Resonator. Various shapes are possible. The desired bandwidth can probably be attained. Tuning will be tricky.

A problem which appears to impede rapid access to applications of the SEM is in the bandwidth of the microwave driving circuitry where various methods of generating very short microwave pulses could be made available. Such methods include the use of traveling wave tubes with control grids allowing pulse operation of both low and high power levels. The disadvantage of the TWT is in the relatively high voltage pulses which are necessary to gate the system on or off.

Another problem lies in the bandwidth limitations of the receiving system used during the research experiments. Although the bandwidths of the IF amplifier can be made extremely wide, it appears to be much simpler to use an RF amplifier instead of an IF amplifier. One low noise traveling wave tube and one traveling wave amplifier tube would provide approximately 75 db gain sufficient to detect an initial signal of -80 dbm. A block diagram of a suggested system is illustrated in Figure 18.

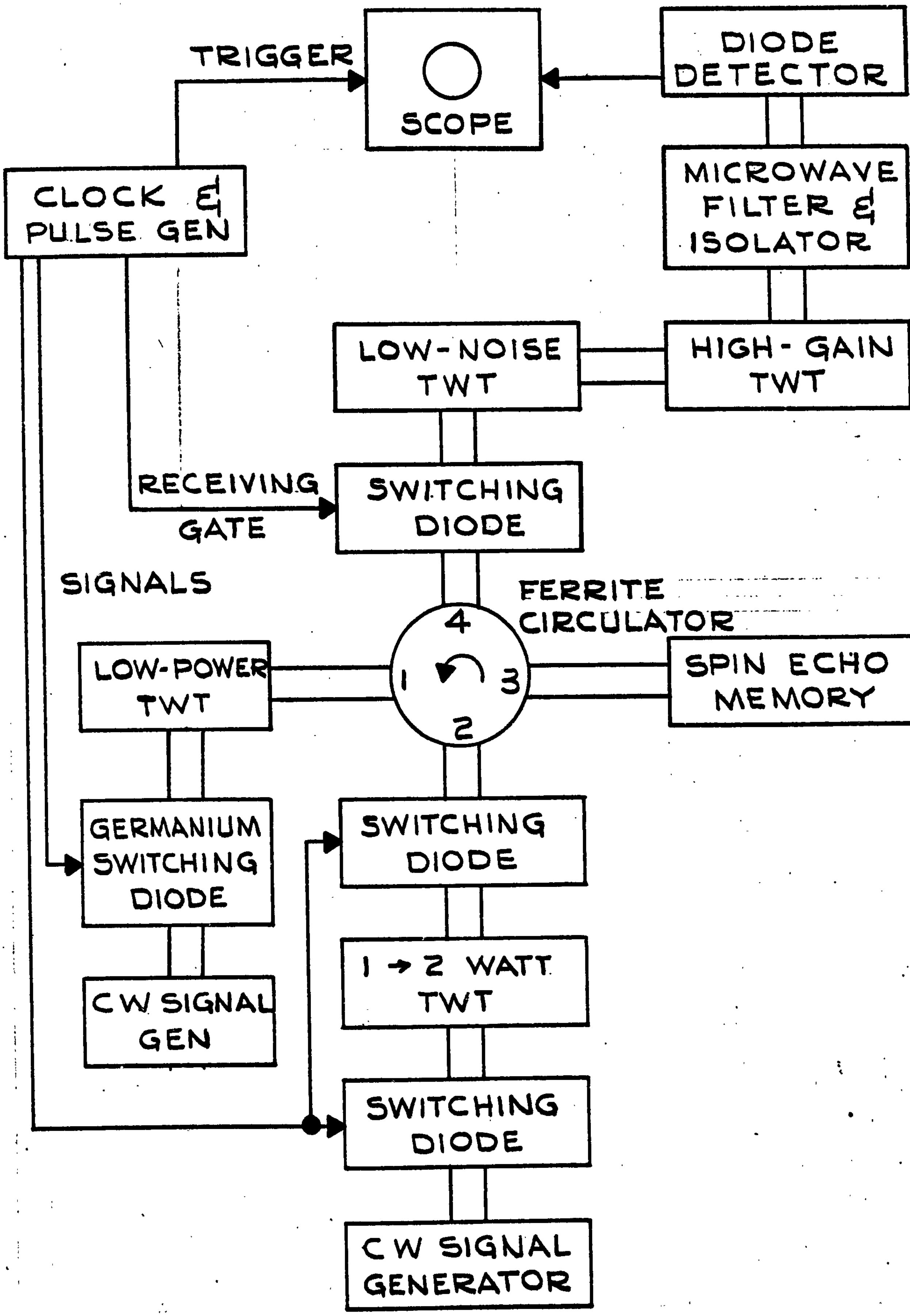
The function of the clock and pulse generator is, of course, to generate the desired pulses. This device would probably be specially built, and with avalanche devices, rise times on the order of 1 to 5 nanoseconds can be obtained.

The traveling wave tubes in both the receiving and transmitting systems are wide band devices (approximately 1000 mc wide) so that the bandwidth of the system would be determined only by the spin echo module. In addition, the germanium switching diodes can switch power levels of up to one watt with a switching time of 1 to 2 nanoseconds. However, the isolation provided is only about 30 db so that more than one in each line may be necessary.

The read out command pulse must be completely off until required so that there is no leakage to the spin echo memory. Port 2 of the circulator requires a short circuit so that the inserted signal is directed to the SEM. Therefore, the RF command pulse is also switched into the power TWT with another switching diode (or set of diodes) allowing the use of the very fast switching capabilities of the germanium diode to be realized.

The switching diode(s) in the receiving system can be operated to prevent feed through of either the signal or the command pulses to the detector. Elimination of the mixer and IF amplifiers allows ease of bandwidth control by use of a microwave filter and isolator.

It is estimated that during a study and development program over a period of six months, with an expenditure of approximately $100,000 for the required manpower and less than $30,000 for the necessary equipment and material, most of these problems could be solved and could indicate the most promising way to realize some of the suggested applications.



TRIGGER
SCOPE
DIODE DETECTOR
CLOCK & PULSE GEN
MICROWAVE FILTER & ISOLATOR
LOW-NOISE TWT
HIGH-GAIN TWT
RECEIVING GATE
SWITCHING DIODE
SIGNALS
FERRITE CIRCULATOR
4
1
3
2
LOW-POWER TWT
SPIN ECHO MEMORY
GERMANIUM SWITCHING DIODE
SWITCHING DIODE
CW SIGNAL GEN
1 → 2 WATT TWT
SWITCHING DIODE
CW SIGNAL GENERATOR

Figure 18

SECTION 7

CONCLUSIONS

It appears to be extremely timely and opportune to propose a development program which would reduce the difficulties of instrumentation and advance towards the realization of some of the applications suggested in the preceding paragraphs, while coincidentally facilitating easier progress of the basic spin echo research activities.

Most of the problems, common to both the research and application of the electron spin echo phenomenon, could be solved by the following steps:

1. Optimization of the microwave structure for the SEM.

2. Increase of overall bandwidth by development of instrumentation as indicated in Section 6.

3. Reduction of the cumulative delays by development of instrumentation as discussed in Section 6.

REFERENCES

I. Lockheed Missiles and Space Company, General Description of the Electron Spin Echo Resonance Phenomenon (ESERP), D. E, Kaplan, 17 January 1964.

II. Lockheed Missiles and Space Company, Notes on Memory Applications on the Electron Spin Echo Resonance Phenomenon (ESERP), D. E. Kaplan, 12 December 1963.

III. Lockheed Missiles and Space Company, Slow Wave Structures for Spin Echo Memory Materials, K. R. Spangenberg, 6 January 1964.

IV. Lockheed Missiles and Space Company, Computer Applications for the Spin Echo Memory Phenomena, M. A. Fischler, 13 November 1963.

1. E. L. Hahn, Physical Review, Vol. 80, 1950, pp 580.
2. H. Y. Carr and E. M. Purcell, Physical Review, Vol. 94, 1954, pp 630.
3. S. Fernbach and W. Proctor, Journal of Applied Physics, Vol. 26, 1955, pp 170.
4. A. G. Anderson et al, Journal of Applied Physics, Vol. 26, 1955, pp 1324.
5. R. G. E. Hutter, Beam and Wave Electronics in Microwave Tubes, VanNostrand, 1960, 537.12/H97
6. J. H. Bryant, Some Properties of Helical Conductors, Electrical Communications, Vol. 31, No. 1, pp 50-56.
7. S. Sensiper, Electromagnetic Wave Propagation on Helical Structures, Proc. IRE, Vol. 43, 1955, pp 149-161
8. L. Brillouin, Wave Propagation in Periodic Structures, McGraw-Hill, New York, 1946.
9. J. E. Nivens, Jr., An Investigation and Application of the Contra-Wound Helix, IRE Transactions P.G.E.D., April 1959, pp 195-202.
10. M. Chodorow and E. L. Chu, Cross Wound Twin Helix for Traveling Wave Tubes, Microwave Lab. Report No. 249, Stanford University, November 1954.
11. RRL, Very High Frequency Techniques, McGraw-Hill, 1947.

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